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EFFECTIVENESS OF AUDIBLE WARNING DEVICES ON EMERGENCY VEHICLES

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FINAL REPORT

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16. Abstract

The primary purpose of this study was to examine the effectiveness of audible warning devices (AWD's) on emergency vehicles in terms of aural detectability. Community noise intrusion and opportunities for AWD optimization were also investigated. The study concentrated upon the three parts of the detection process: (1) Source (siren); (2) Path (distance and structures); and (3) Receiver (the human detection process in the presence of noise). Measurements were made of sirens, automobile insertion loss, and human detection performance in real-life and simulated situations. Warning effectiveness distances were calculated for three representative situations: (1) Rural environment with vehicle windows closed and radio on; (2) Urban environment with vehicle windows open and radio off; and (3) Suburban environment with vehicle windows open and radio off. It was concluded that reliance on present audible warning devices to warn drivers in traffic is not justified. To be loud enough to warn in all orginary circumstances, the sound level of audible warning devices would have to be increased greatly -- producing intolerable community noise. During emergency-vehicle driver training, drivers should be taught about the short detection distances commonly encountered. Present audible warning devices can be improved; more uniform horizontal forward radiation and higher frequency sounds would increase detectability. This analysis procedure can provide the basis for an objective measure of audible warning device performance. Such a performance measure could be incorporated into a recommended practice.

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Audible Warning Devices, Sirens,
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PREFACE

This report presents the results of a study to examine the effectiveness of ~~our~~ audible warning devices on emergency vehicles in terms of aural detectability. This report was prepared by Bolt, Beranek and Newman under the technical coordination of the Society of Automotive Engineers (SAE) who were under contract to the Transportation Systems Center of the U.S. Department of Transportation in Cambridge, Mass. The SAE Vehicle Sound Level Committee selected the following panel members who provided guidance and assistance towards the successful completion of this project: Mr. Warren M. Heath (Chairman), Mr. Paul Olson, Mr. Thomas L. Quindry, Mr. Fred L. Seebinger, and Mr. Roy M. Terry.

This study has involved a great deal of measurement, analysis, and discussion. The authors are grateful to the following members of the BBN staff, who contributed to this study:

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and Mr. Richard Shu

Mr. William M. Bower - Smith and Wesson
Product Manager.

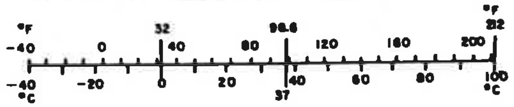
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SUMMARY

Under contract to the Society of Automotive Engineers, Bolt Beranek and Newman Inc. conducted a study on audible warning devices (AWDs) for emergency vehicles. The primary purpose of the study was to examine the effectiveness of AWDs in terms of aural detectability. Community noise intrusion and opportunities for AWD optimization were also investigated. However, the subjects of identification of the AWD sound and hearers' reaction time were not treated.

The study concentrated upon the three parts of the detection process:

-> Source (siren)

-> Path (distance and structures)

-> Receiver (the human detection process in the presence of noise).

As a result, extensive measurements were made of sirens, automobile insertion loss, and human detection performance in real-life and simulated situations.

Major findings of this study are

- The audible warning devices studied radiated most of their sound directly forward and at frequencies below 2000 Hz.
- The interior noise in automobiles and commercial vehicles, travelling at high speed with the radio on and windows open, reached high levels in the same frequency range -- below 2000 Hz.
- The acoustic insertion loss of the vehicles studied was greater at higher frequencies, although there was an indication of a notch near 2000 Hz.
- Experiments showed persons seated in automobiles could not reliably indicate the direction from which an audible warning device was being sounded.
- A validation experiment, conducted under simulated driving conditions in a real car, showed that the temporal pattern of the signal is not important, but that the frequency content is important. This experiment also suggested that the driving task increased the signal-to-noise ratio required for reliable detection.

Warning effectiveness distances were calculated for three representative situations:

-> Rural environment with vehicle windows closed and radio on

-> Urban environment with vehicle windows open and radio off

-> Suburban environment with vehicle windows open and radio off.

The warning effectiveness distances -- the distance at which reliable detection occurs - ranged from 450 ft to an impractically low 3 ft.

It was concluded that reliance on present audible warning devices to warn drivers in traffic is not justified. To be loud enough to warn in all ordinary circumstances, the sound level of audible warning devices would have to be increased greatly -- producing intolerable community noise. During emergency-vehicle driver training, drivers should be taught about the short detection distances commonly encountered.

Present audible warning devices can, however, be improved; more uniform horizontal radiation in the forward direction and higher frequency sounds would increase their detectability.

The analysis procedure used in this study can provide the basis for an objective measure of audible warning device performance. Such a performance measure could be incorporated into a recommended practice.

1. INTRODUCTION

This study was performed to determine how and why sirens are or are not detected in traffic. Sirens of emergency vehicles are intended to supplement warning lights in notifying people that an emergency vehicle is approaching and that they have to get out of the way. Because it is an emergency vehicle, it is operating in an abnormal manner with regard to the other traffic; e.g., it may be travelling faster and/or not obeying the accepted rules of the road. In addition, the emergency vehicle is demanding priority over other road users; its approach requires other motor vehicles, cyclists, and pedistrians to clear a path.

Unfortunately, sirens as audible warning devices* on emergency vehicles do not always attract the attention of drivers. Experienced police officers and ambulance drivers report that some drivers do not hear the sirens early enough to ensure safety. The problem is further exemplified by the greater incidence of fatal accidents involving emergency vehicles [1], in comparison with all other road vehicles.

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*Throughout this report, the word "sirens" means "audible warning devices."

On the other hand, a study by a Maine policeman [ibid] documents the concern of police officials, emergency vehicle operators, and the general public about what is considered excessive and unwarranted use of sirens.

In this report, the elements affecting the detection of audible warning devices are organized into separate phases. Figure 1 illustrates these phases and the links in the chain of properties and actions that influence the identification of and response to the AWD.

Figure 1 illustrates the difficulties of obtaining a simple solution to the problem of producing an optimally effective audible warning device. Different parties on the road are affected to a different degree because of the variability of individual situations. For example, the propagation losses for a pedestrian are influenced by atmospheric and geometric factors such as distance, buildings and other barriers, and reflecting surfaces. An automobile driver, however, experiences far greater transmission loss of the siren sounds because of his vehicle structure. Furthermore, the masking noise (the background sounds over which the receiver must detect the siren) will generally be higher for a driver of a truck than a car. The driver also is exposed to discretionary noise from radio or tape systems.

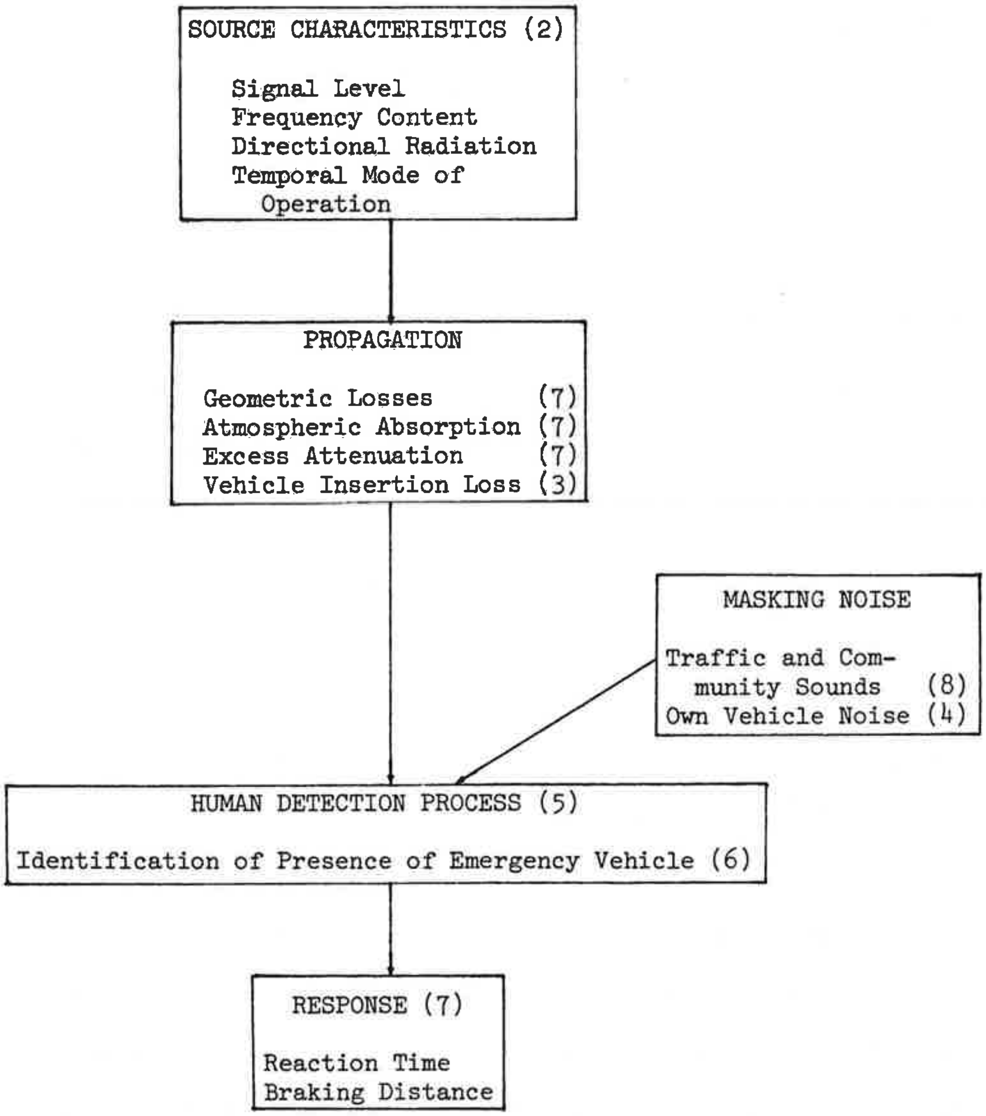


FIG. 1. STEPS IN DETECTION OF AND RESPONSES TO EMERGENCY AWD's. (Numbers in parentheses refer to sections in this report).

Thus, "optimally" must be defined in terms of the interactions of source levels, propagation losses, and background noise levels. Engineering efforts directed at any one factor in isolation are unlikely to produce meaningful improvements. For instance, reducing the insertion loss of a vehicle at a particular frequency is of no avail if a siren produces little energy at that frequency or if background noise levels are especially high at that frequency. Raising the energy levels of sirens will likewise be ineffective unless favorable propagation loss and background noise conditions prevail in the same frequency range.

A key objective of the current study was the quantification of the requirements for detection of the siren in terms of all these phenomena. The measurements reported in this study were intended to produce quantitative information for representative values of all the aspects of the problem, as defined in Fig. 1. It was also felt that no useful purpose would be served by considering particular sirens or vehicles. This view was adopted when it became clear from measurements that variability in the ratio of siren signal levels to background noise levels in actual vehicles could be enormous. This variability made it impractical to deal with specific cases, since no reasonable number of them could have represented the range of conditions likely to be encountered in different traffic situations. Therefore, the approach adopted was to study idealized cases, based wherever possible on averaged data.

The treatment of the detection of siren sounds used in this report was based on the Theory of Signal Detectability [2], which views human perception as a process in which decisions based on uncertain sensory information are made under conditions of risk. The theoretical model that follows from this view predicts how a hypothetical ideal observer would make decisions under specified conditions. If human behavior then diverges from ideal behavior, it is possible to formulate testable hypotheses to explain the differences between real and ideal behavior.

The descriptive part of the model postulates that detection decisions have two components: perceptual sensitivity and response bias. As an example of the influences of completely non-sensory influences upon the apparent gross detectability of a warning signal, consider the following situation. A driver, in a hurry to reach his destination, is immersed in traffic flow when he first hears something that might be a warning signal. He can continue on his way if he decides that what he has heard is not a warning signal, or he can pull over to the side of the road to yield the right of way.

Clearly, there are four outcomes attached to the driver's two decisions (YIELD and CONTINUE). They are summarized below:

	ACTUAL SITUATION	
DRIVER'S DECISION	EMERGENCY VEHICLE ABSENT	EMERGENCY VEHICLE PRESENT
CONTINUE	Correct Rejection	False Rejection
YIELD	False Detection	Correct Detection

If the driver decides to continue on his way and no emergency vehicle is present (correct rejection), he will reach his destination without unnecessary delay. If he does pull over to the side of the road and no emergency vehicle is present, he needlessly disturbs traffic flow and wastes his time (false detection). If he does not yield the right-of-way and an emergency vehicle is in fact approaching, he risks a collision or a traffic citation (false rejection). If he does yield the right of way and an emergency vehicle is approaching, he properly speeds the emergency vehicle on its way (correct detection).

It is obvious that the risks and rewards associated with the four decision outcomes will have a major influence on the apparent detectability of a warning signal. The probabilities of false detections and correct detections may be drastically changed merely by increasing or decreasing the driver's feeling of urgency to arrive at his destination, or his a priori information about the likelihood of observing emergency vehicles in certain areas (e.g., near hospitals or fire stations).

The Theory of Signal Detectability provides a theoretical basis for independent estimates of the sensory and non-sensory components of gross detection performance. In particular, a statistic (d') has been developed that reflects solely the sensory contribution to human signal detection. The "detectability" of an acoustic signal may be defined in terms of the sensitivity to that signal required for an observer to report its presence with given correct detection and false detection rates. The formal measure of signal detectability is given mathematically by the equation:

$$d' = \frac{\eta S(\omega)^{\frac{1}{2}}}{N} ,$$

where η is an expression of the efficiency of a human observer relative to that of an ideal energy detector, S is the signal level in a 1/3-octave band, N is the background noise level in the same 1/3-octave band, and ω is the 1/3-octave bandwidth. This equation is used in the validation experiment described in Sec. 5.

The approach of this study was to examine in detail each of the various aspects of the process of detection of emergency vehicle sirens. Measurements were made of interior noise and insertion loss of automobiles and commercial vehicles and of the sound characteristics of available sirens. Experiments to determine the relevant value of the detectability coefficient d' were conducted and the appropriate values of signal-to-noise ratio were determined. Other experiments were conducted on the driver's ability to detect the direction of the emergency vehicle by listening to its siren sound.

These data were then used to establish certain representative model situations. The results of these studies, expressed as warning effectiveness distances, were used to examine the characteristics of the detection process.

2. SOURCE CHARACTERIZATION

2.1 SURVEY OF MANUFACTURERS OF AUDIBLE WARNING DEVICES

As a first step in determining the properties of audible warning devices, data were solicited from manufacturers by mail. Two questionnaires, one for electronic devices and one for electromechanical devices, were designed to obtain such information as cost, number in use, typical location on emergency vehicle, signal type, and signal strength. The questionnaires were designed to yield useful information while being easy to complete. A list of 66 manufacturers was prepared using such publications as The Thomas Register, the Industrial Product Directory, and the Yellow Pages. The questionnaires were mailed, with an enclosed stamped and pre-addressed return envelope, under a cover letter on The Society of Automotive Engineers' letterhead stationery. Completed questionnaires were received from 21 companies. The results of the returned questionnaires are summarized in Table 1.

2.2 DISCUSSION OF COMMERCIALLY AVAILABLE SIRENS

The electronic siren (signal generator, amplifier, and loudspeaker horn) has largely replaced the electromechanical coaster siren as the predominant audible warning device used on police, fire, and rescue vehicles. The electronic units produce comparable (or higher) sound levels, together with a greater

TABLE 1. SUMMARY OF RESULTS FROM QUESTIONNAIRE SURVEY.

P = POLICE
F = FIRE
A = AMBULANCE
R = ROOF
F = FENDER
UH = UNDER HOOD

BG = BEHIND GRILLE
S = STEADY
W = WAIL
Y = YELP
H = HI-LO

* = 2 SPKRS - EACH SPKR WILL HANDLE ONLY 100 W.
** = LOW IS 1 SPEAKER HIGH IS 2 SPEAKERS
† = CALIFORNIA HIGHWAY TEST AVAILABLE

ELECTRONIC DEVICES

MANUFACTURER	MODEL NO.		# UNITS IN USE	COST/ UNIT	YEAR INTRODUCED	TYPICAL APPLICATION	LOCATION ON VEHICLE	SIGNAL CHARACTER	FREQUENCY RANGE (Hz)	CYCLING RATE (CYCLES/MIN)			MAX OUTPUT POWER AMP WATTS RMS	MAX. PWL dB re 10^{-12}	MAX SPL AT 100 FT			
	AMP/CONTROL	SPEAKER								WAIL	YELP	HI-LO			0°	45°	90°	180°
ALERTING COMMUNICATOR OF AMERICA	ALERTRON			300-		P, F, A	R	W, Y, H, PULSE	400-1200	6	60	30 + PULSE 80	110	140.6 ?	100			
(SOLD UNDER PRIVATE LABELS) CARSON MANUFACTURING CO., INC.	SA 300	D-50				P, F, A	R, F, BG	W, Y, H	260-590	12	175	60	200*		104** 112	†	†	†
"	SA 400	D-50				P, F, A	R, F, BG	W, Y, H, 3-TONE AMB	650-1250	12	175	60	200*		104** 112	†	†	†
R.E. DIETZ CO.	14-460	14-460	500	320	1974	P, F, A	R, F	W, Y, H, MANUAL WAIL	450-780 H/L 1100-820	15	85	85	50 @ 13V. IN		96.5	91		
DUNBAR-NUNN	800	ANY SPKR	15,000	265	1970	P, F, A	R, BG	W, Y, H H TO BE DISCONT.	500-1450	11.5	845	56	190 @ 13V. IN					
EMERGENCY VEHICLE EQUIPMENT SERV.	ES-1	ESS-1				P, F	UH	W, Y, H OPTIONAL	650-1300	20	190	48	60		92	87.5		
"	ES-1	HPC-75				P, F	R	W, Y, H OPTIONAL	560-1300	20	190	48	60		97	97		
"	ES-1	HPR-75				P, F	R, UH	W, Y, H OPTIONAL	550-1300	20	190	48	60		96.5	90		
FEDERAL SIGN & SIGNAL CORP.	PA-1000	CP100		450		P, F, A	R	S, W, Y, H	500-1500	10	180	50	200					
ITT ELECTRONICS, INC.	IT-236A	HPR-75	NOT CURRENTLY MARKETED			P, F, A	R	W, Y, H	400-1200	7	60		145 (2 SPKR)		102			
INDUSTRIAL ELECTRONICS SERVICE CO.	SPR73-B	2 EA. CSL-25	4000	234.50 LESS SPKRS	1973	P, F, A	R, F, UH	S, W, Y, H, MAN & FAST W	200-1600	8-12 40-FAST	160-200	50	140		106	100		
"	SPR73-B	1 EA. CSL-25	4000	234.50 LESS SPKR	1973	P, F, A	R, F, UH	S, W, Y, H, MAN. & FAST W	200-1600	8-12 40-FAST	160-200	50	80		100	95		
"	SPR75-A	1 EA. CSL100		NOT SET	1975	P, F, A	R, F, UH	S, W, Y, H, MAN. & FAST W	200-1600	8-12 40-FAST	160-200	50	105		128 (10 FT)	120 (10 FT)		
"	SPR75-A	2 EA. CSL 100		NOT SET	1976	P, F, A	R, F, UH	S, W, Y, H MAN. & FAST W	200-1600	8-12 40-FAST	160-200	50	180					
SIGNAL STAT CORP.	STAT X	381				P, F, A	R, UH	W, Y, H	600-3500	12	180 ?	60	90		100			
SIRCHIE FINGER PRINT LABORATORIES, INC.	BFN-2000	BFN 102		245		P, F, A	R, F	S, W, Y, H	500-1500	10	130	45	50		93** 103	90 96		
SMITH & WESSON	MAGNUM 4	551	30,000	195 SIREN & 50 SPKR	1969	P, F, A	R	W, Y PA & RADIO	400-1200	10	120	60	100 @ 13.6V. IN 150% 2 SPKR					
VISTA MANUFACTURING CO., INC.	V 150					P, F, A, HELICOPTER	R											

ELECTRO-MECHANICAL DEVICES

MANUFACTURER	MODEL NO.	# UNITS IN USE	COST/ UNIT	YEAR INTRODUCED	TYPICAL APPLICATION	LOCATION ON VEHICLE	FREQUENCY RANGE (Hz)	CYCLING RATE (CYCLES/MIN)	MAX OVERALL PWL dB re 10^{-12}	MAX SPL AT 100 FT			
										0°	45°	90°	180°
ALERTING COMMUNICATORS OF AMERICA	COMMANDER		350		P, F, A	R	300-700	MANUAL	146.5	106			
"	DUPLO	50,000	95	1925	P, F, A	R, F, UH	400-1500	MANUAL	132	116 (6 FT)			
"	MONO	100,000	70	1920	P, F, A	R, F, UH	500-1800	MANUAL	126	110 (6 FT)			
THOMAS INDUSTRIES BENJAMIN DIV.	KH 9144			1974	HEAVY EQUIPMENT	R, OTHER	400-600	AUTO - 90 (BACK-UP WARN)		100 (10 FT)	86	95	90
FEDERAL SIGN & SIGNAL CORP.	Q		375		F, A.	R, F, UH, IN FRONT OF OR BUILT INTO GRILLE	1100	MANUAL		126 (10 FT)			

MECHANICAL DEVICES

MANUFACTURER	MODEL NO.	# UNITS IN USE	COST/ UNIT	YEAR INTRODUCED	TYPICAL APPLICATION	LOCATION ON VEHICLE	FREQUENCY RANGE (Hz)	CYCLING RATE (CYCLES/MIN)		MAX. SPL AT 100 FT			
										0°	45°	90°	160°
AMF/HARLEY-DAVIDSON MOTOR CO.	68				P	LEFT SIDE BY REAR TIRE OR FRONT		MANUAL			100 - 105		

variety of sounds, and they consume much less electrical power than the motor-driven coaster sirens.

The results of the survey indicated that although there are many models of electronic sirens, there is surprisingly little variety in the available products. There are a number of reasons for this commonality. First, most of the market is concentrated in the hands of five manufacturers [3] and one key component, the loudspeaker driver, is supplied by only two manufacturers [4]. Secondly, all of the manufacturers have nearly identical electronic designs in order to comply with the following set of design considerations:

-> The available voltage supply is that of the vehicle, and thus is not changeable [it is between 13 and 16 V(DC), with the engine running].

-> All of the amplifiers are driven into saturation at the output stage. The wave abruptly "clips" and resembles a square wave rather than a sinusoid. This characteristic assures that the amplifier supplies nearly the maximum possible electric power to the speaker load and provides a signal rich in harmonic content.

-> Space requirements limit the size of the loudspeaker horns. Since horn length has direct bearing on the acoustic load impedance seen by the loudspeaker driver, the effective frequency range is limited to above 500 Hz. Frequently, two loudspeakers are connected to a single amplifier, doubling the acoustic power at the expense of a directional radiation pattern.

-> Most units concentrate their signal energy near the maximum of human hearing acuity -- from 1000 to 3000 Hz.

-> Because the signals produced must be recognizable as warnings, only three signal types exist: the <u>wail</u>, familiar in North America as the sound of the traditional coaster siren; the <u>yelp</u> or "fast wail"; and the <u>hi-lo</u>, the traditional two-tone European warning signal.

Because of the similarities among the products available, a representative sample of electronic units and loudspeakers was chosen for measurement. The specific choices were intended to span the range of available operating frequencies, duty cycles, power outputs, and speaker-power-handling capabilities from among the key manufacturers.

The results of the measurements confirmed that the products are quite similar in performance.

2.3 MEASUREMENTS OF SIREN CHARACTERISTICS

The data supplied by manufacturers were supplemented by measurements of siren signal characteristics for the six sirens listed in Table 2. These sirens were selected to represent the range of frequencies and sound power outputs available among the most popular models in use. Because electronic sirens are currently in such widespread use and because they are capable of producing a greater variety of sounds, five of the six units examined were of the electronic type. The sixth was a standard electromechanical coaster siren.

The measurements were performed in a semianechoic chamber -- a large room with highly sound-absorbing walls and a hard concrete floor. The sirens were each mounted identically on the roof of an automobile.

TABLE 2. LIST OF SIRENS WHOSE CHARACTERISTICS WERE MEASURED.

Siren Manufacturer	Siren Model No.	Speaker Manufacturer	Speaker Model No.	Signal Modes Wail	Yelp	Hi-Lo
1. Federal Signal	PA 200	Federal Signal	CP-25	X	X	X
2. Federal Signal	PA 200	Federal Signal	CP 100	X	X	X
3. Dunbar-Nunn	Unitrol 800	Atlas Sound	HPR 370	X	X	X
4. Carson Ind.	SA 310	Carson Ind.	390R	X	X	X
5. Carson Ind.	SA 410	Carson Ind.	390R	X	X	X
6. B&M Siren	S8-M9	(electromechanical)		X	-	-

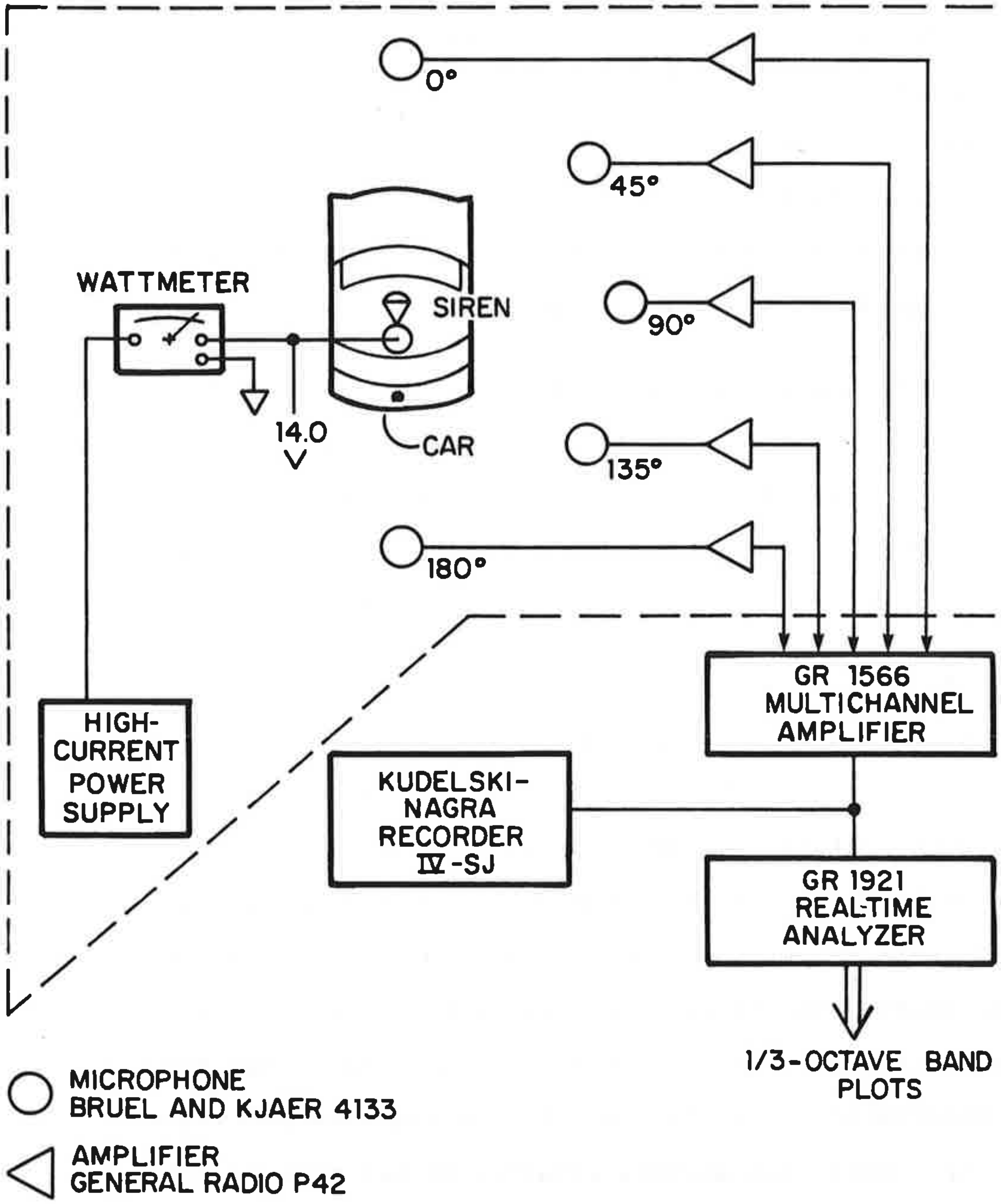
Measurement microphones were positioned at 45-degree increments on a 12 ft (3.6-m) radius from the horn center at the height of the horn. There were five positions: 0 degrees (directly in front of the siren), 45 degrees, 90 degrees, 135 degrees, and 180 degrees (directly behind the siren). (See Fig. 2 and Appendix.)

The microphone signals were recorded on magnetic tape. At the same time, a real-time analyzer was used to measure the long-term energy average sound pressure levels in 1/3-octave bands. The type recordings were subsequently used for detailed statistical analyses and as stimulus material for the psychoacoustic tests described in Sec. 5.

A high-current regulated DC power supply was used for the power source for the electronic sirens, and the voltage supplied was maintained at 14.0 V. Since the current requirements for the coaster siren were too great for the regulated supply, an automotive battery was used for this test.

2.4 DISCUSSION OF MEASUREMENT RESULTS

Analysis of the signals produced by a siren is complicated by the signals' complexity. The sound of a siren can be thought of as a family of harmonics that is frequency-modulated by the cycling pattern (e.g., wail, yelp, or hi-lo). Thus, the siren



DISTANCE FROM SIREN CENTER TO
ALL MICROPHONES: 12.0 ft (3.6m)

FIG. 2. INSTRUMENTATION FOR ACOUSTIC MEASUREMENTS OF SIRENS.

signal varies in time, frequency, amplitude, and direction. The difficulty lies in characterizing the four-dimensional variable representing the signal. To do so, each cycling mode of each siren was treated as if it were a source. The sound level at the 45-degree measurement location, relative to that at 0 degrees, was used as a measure of source directivity. The balance of the analysis concentrated on the on-axis signals.

The tape recordings of the siren signals were statistically analyzed using a Hewlett-Packard 1/3-octave band real-time analyzer coupled to a PDP-8 minicomputer. Percentile levels and energy mean levels (L_{eq}) were calculated for each 1/3-octave band. The integration time for the analyzer was 0.1 sec.

Typical cumulative distributions of sound levels are plotted in Fig. 3 for the three operating modes of the Federal PA200 siren with a CP100 speaker. These distributions illustrate some important characteristics of the three cycling modes. First, more acoustic energy is radiated by the yelp and wail modes than by the hi-lo mode. Second, the degree of variability in the signal is proportional to the cycling time of the mode. The wail mode shows the greatest spread. The hi-lo mode shows a similar, though less exaggerated, distribution. As one would suspect, the distribution of these two signals illustrates two more or less steady sound levels, with a transition region between them. For example, the hi-lo signal spends about 30% of its time at approximately 117 dB(A), about 20% of its time at approximately

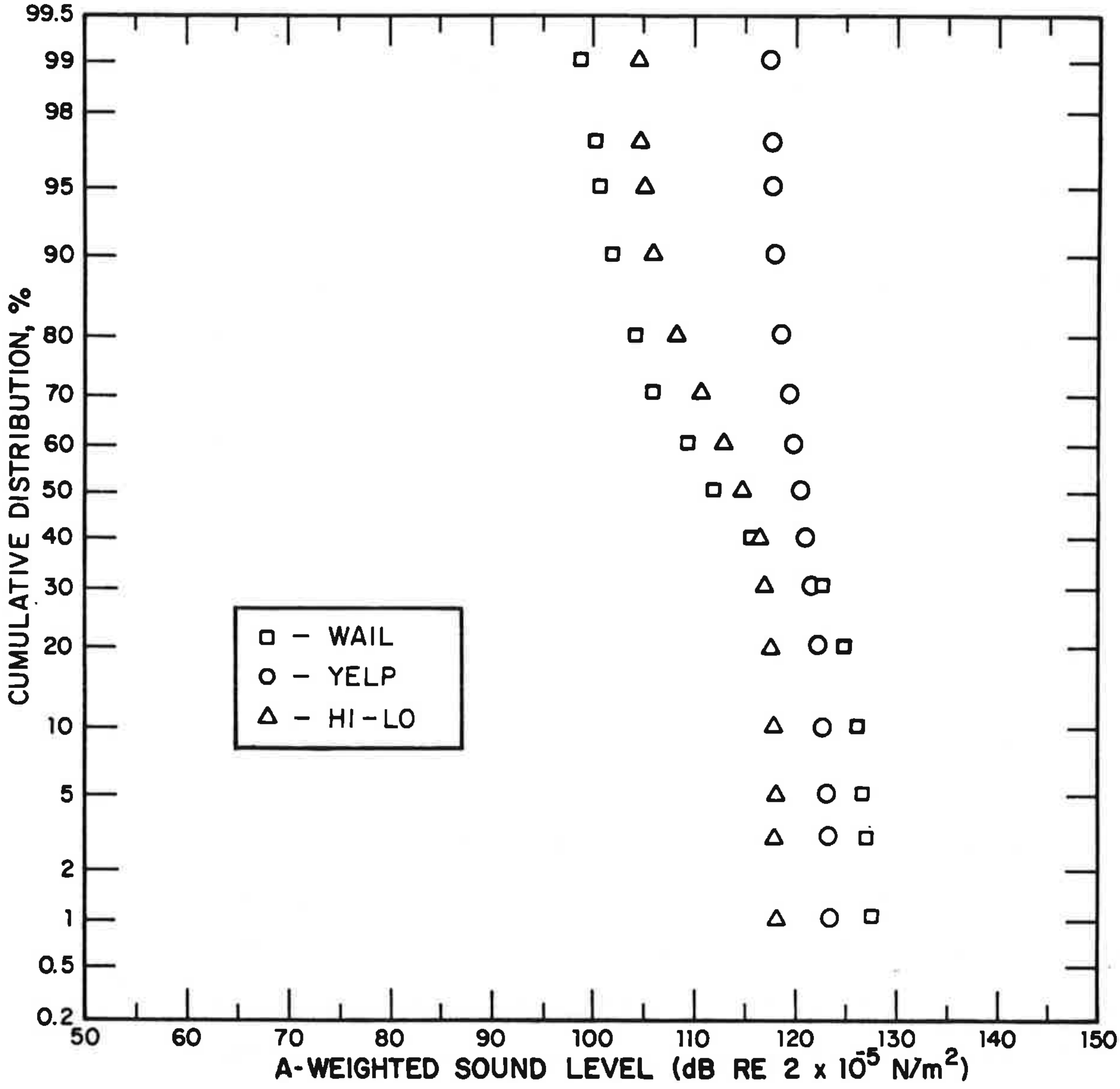


FIG. 3. CUMULATIVE DISTRIBUTIONS OF SOUND LEVELS FOR THE THREE OPERATING MODES OF A FEDERAL SCIENTIFIC PA200 SIREN WITH CP100 SPEAKER; 0° AT 12 ft (3.6m).

105 dB(A), and the rest of the time in transition. In contrast, the yelp mode has a nearly Gaussian distribution (i.e., is a straight line), with a small variance, partially because the 0.1-sec averaging time of the real-time analyzer conceals the rapid periodicity of the yelp. Similar level distributions were observed for the other sirens considered.

These results can be summarized as follows: the greatest acoustic energy is radiated by the wail and yelp modes, which are nearly equal in this respect; the greatest variability is exhibited by the wail mode; and the greatest constancy in level is embodied in the yelp mode.

Further analysis of the yelp signal indicates that its 1/3-octave band levels also have Gaussian distribution. Figure 4 shows the cumulative distributions for the two 1/3-octave bands with the greatest long-term acoustic energy (the "maximum bands" -- 1600 Hz and 3150 Hz) plus, again, the cumulative distribution of the A-weighted levels. Note that the 1/3-octave band distribution, like that for the A-weighted level, are straight-line (Gaussian) distributions. In contrast, Fig. 5, for the wail mode of operation, shows that the distributions of levels in the maximum bands are not Gaussian distributions. The distribution for the 1600 Hz 1/3-octave band shows, for instance, that the unit radiates significant energy in this band during 30% of the wail duty cycle, and almost no energy the rest of the time.

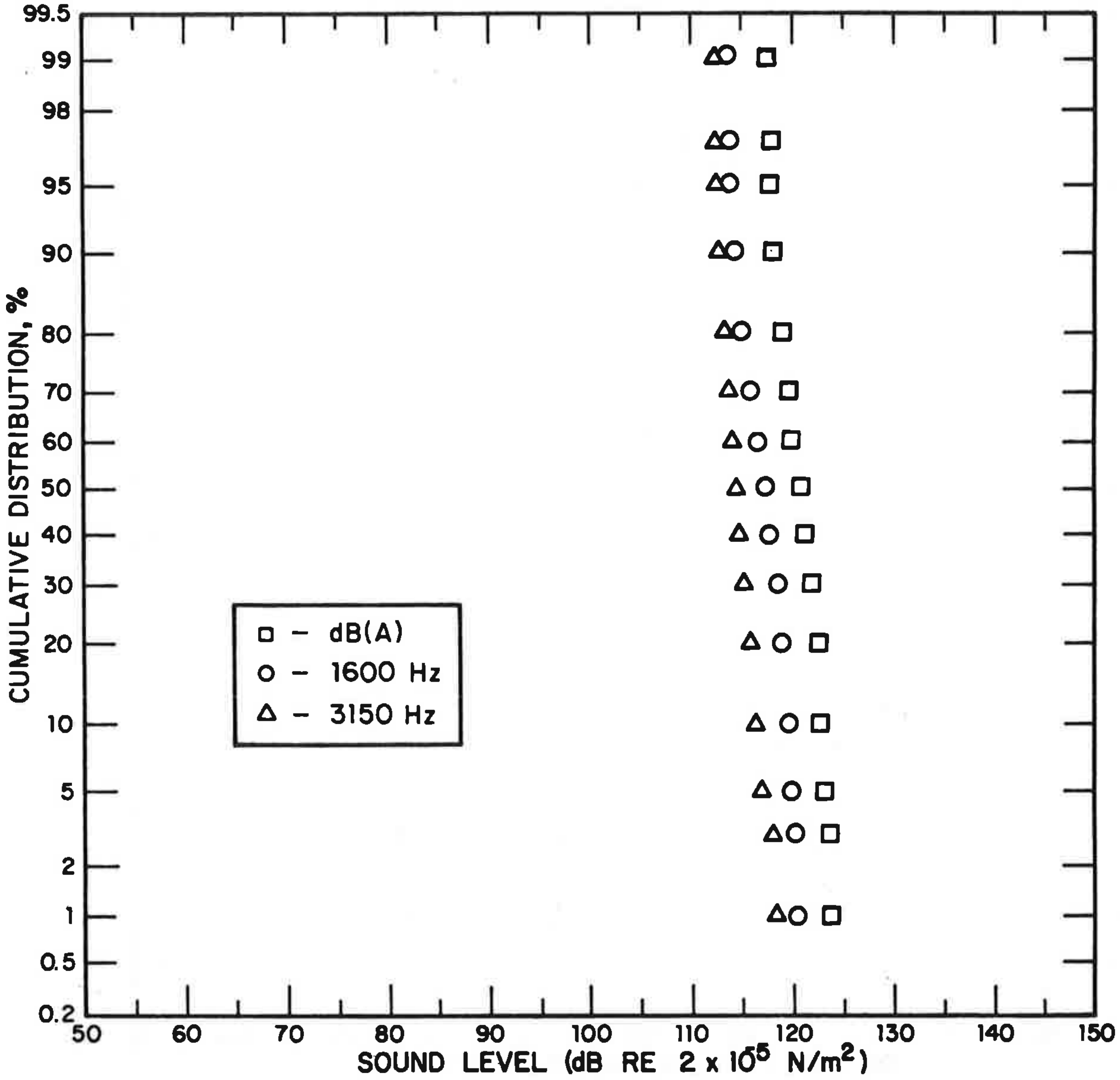


FIG. 4. CUMULATIVE DISTRIBUTIONS OF TWO MAXIMUM-BAND LEVELS AND THE A-WEIGHTED SOUND LEVELS FOR THE YELP MODE - FEDERAL SCIENTIFIC PA200 SIREN WITH CP100 SPEAKER; 0° AT 12 ft (3.6m).

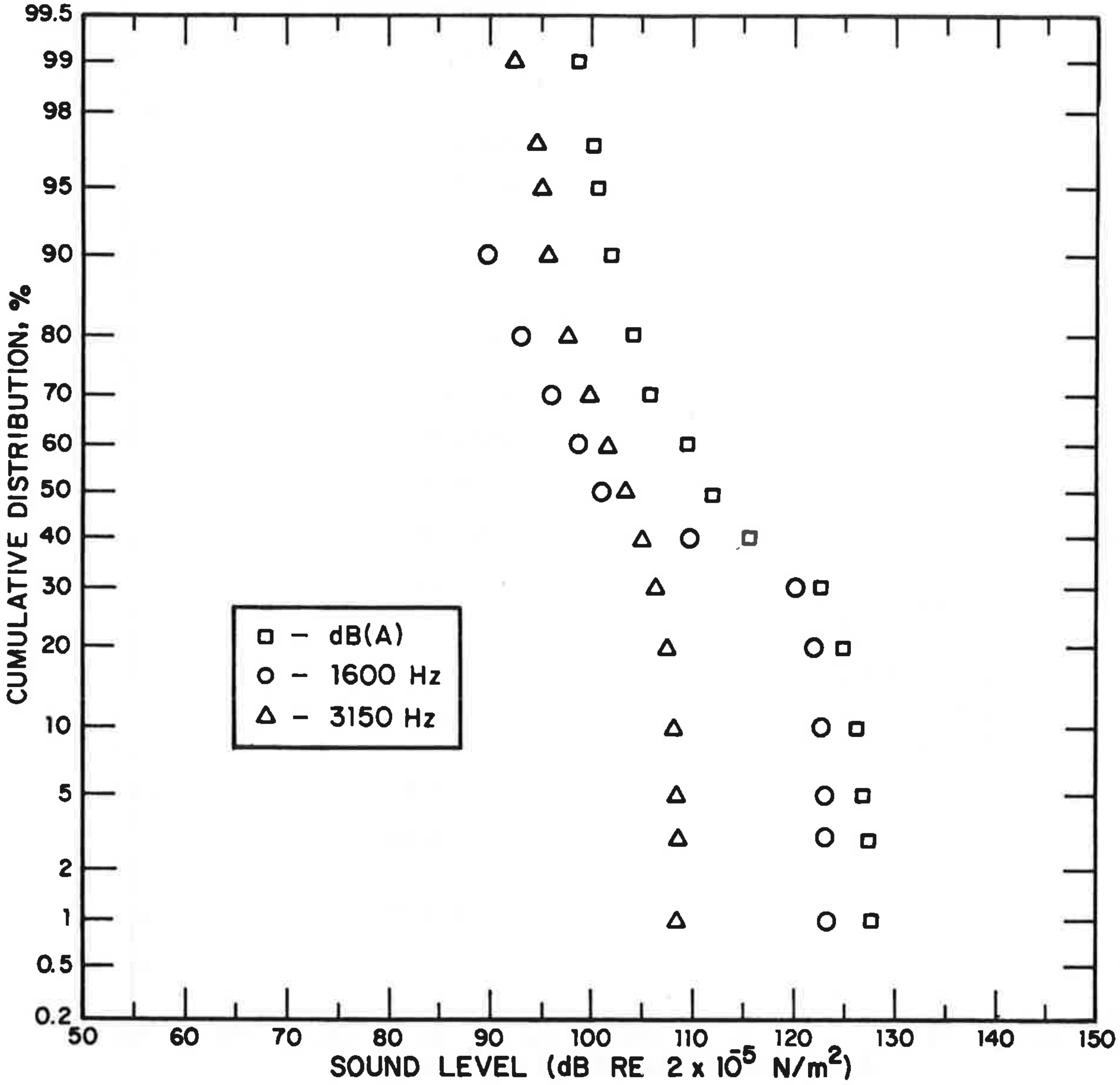


FIG. 5. CUMULATIVE DISTRIBUTIONS OF TWO MAXIMUM-BAND LEVELS AND THE A-WEIGHTED SOUND LEVEL FOR THE WAIL MODE - FEDERAL SCIENTIFIC PA200 WITH CP100 SPEAKER; 0° AT 12 ft (3.6m).

Similar results for the other electronic sirens indicated that the total acoustic energy radiated during the yelp mode is very nearly constant. Hence, it can be considered, to a first approximation, to be a steady-state acoustic power source: a family of harmonics that cycles through the range of maximum human hearing acuity. The yelp is a special signal because it is temporally stationary.

The relationship between the maximum 1/3-octave band level and the A-weighted Leq is shown in Table 3 for all cycling modes of all the electronic sirens measured. The table shows that differences between the long-term A-weighted energy average value and long-term energy average maximum band level is nearly fixed for a given cycling mode.

The deterministic nature of the signals indicates that all three are statistically stationary, though two (wail and hi-lo) exhibit considerable temporal variability. Consequently, the three modes of operation have been modeled by a characteristic level and long-term energy spectrum. Figures 6-9 give these idealized spectra for each cycling mode, radiated at 0 degrees and 45 degrees. The spectra for the electronic sirens are a least-squares fit to the (L_{eq}) values of each 1/3-octave band level for all the measured devices.

TABLE 3. ACOUSTIC PROPERTIES OF ELECTRONIC SIRENS AT 0°; 12 FT (3.6m)

	YELP			WAIL			HI-LO		
	Level in Max. Band	L_{eq} dB(A)	Difference dB	Level in Max. Band	L_{eq} dB(A)	Difference dB	Level in Max. Band	L_{eq} dB(A)	Difference dB
Federal PA200 w/CP25 Speaker	115.0	118.0	3.0	115.0	118.3	3.3	108.8	110.7	1.9
Federal PA200 w/CP100 Speaker	117.2	120.5	3.3	117.3	120.8	3.5	112.8	115.0	2.2
Dunbar Nunn Unitrol 800 w/ ATLAS HPR370 Speaker	115.3	119.6	4.3	115.5	120.1	4.6	110.4	113.2	2.8
Carson SA310 w/390R Speaker	110.3	113.3	3.0	108.0	113.1	5.1	110.5	114.0	3.5
Carson SA410 w/390R Speaker	117.8	119.4	1.6	116.9	118.9	2.0	112.3	114.8	2.5
Average	115.1	118.2	3.04	114.5	118.2	3.7	111.0	113.5	2.6
Spread	7.5	7.2	2.7	9.3	7.7	3.1	4.0	4.1	1.6

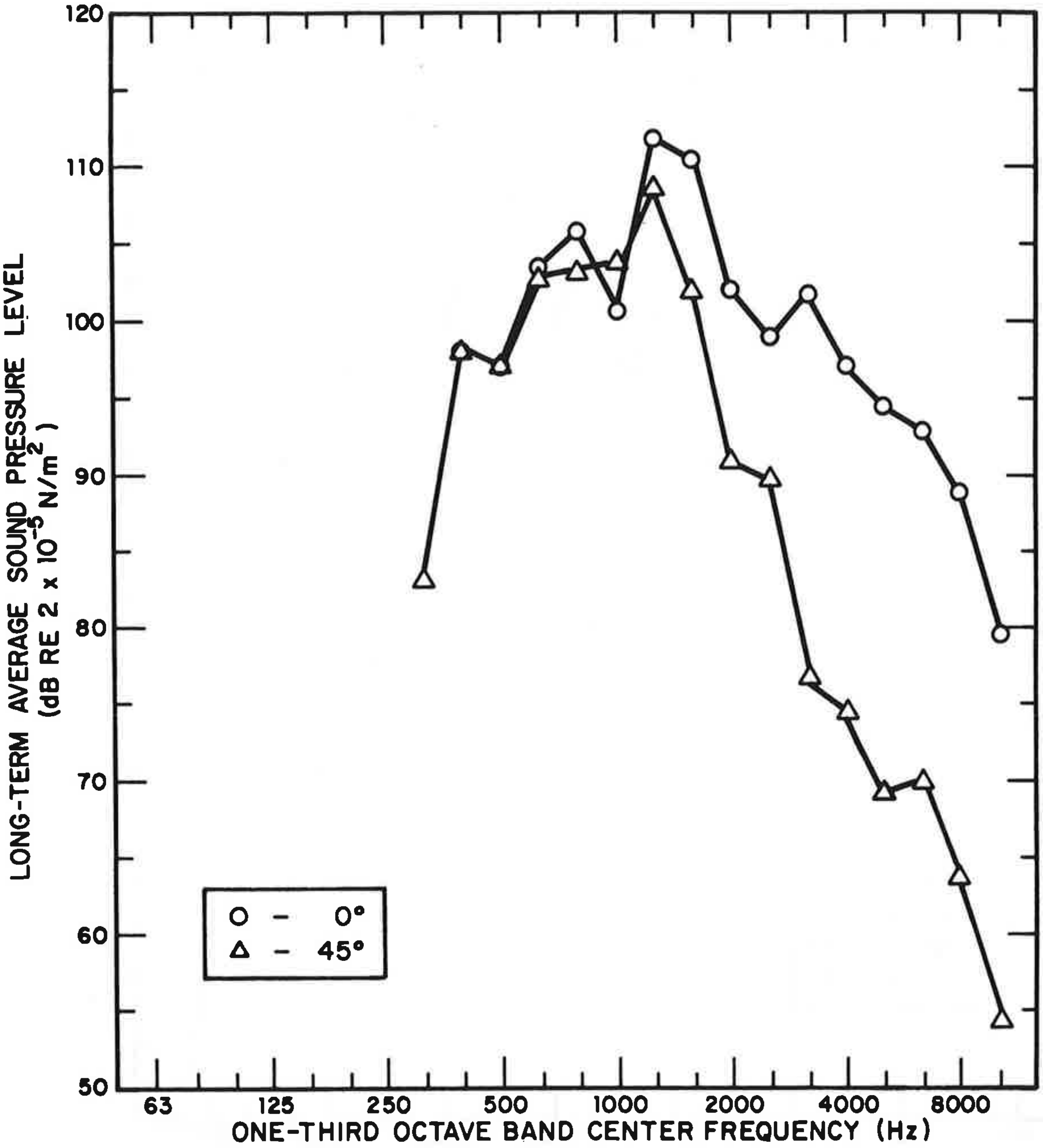


FIG. 6. LEAST-SQUARES FIT TO SOUND-PRESSURE LEVEL SPECTRA OF ALL ELECTRONIC SIRENS – WAIL.

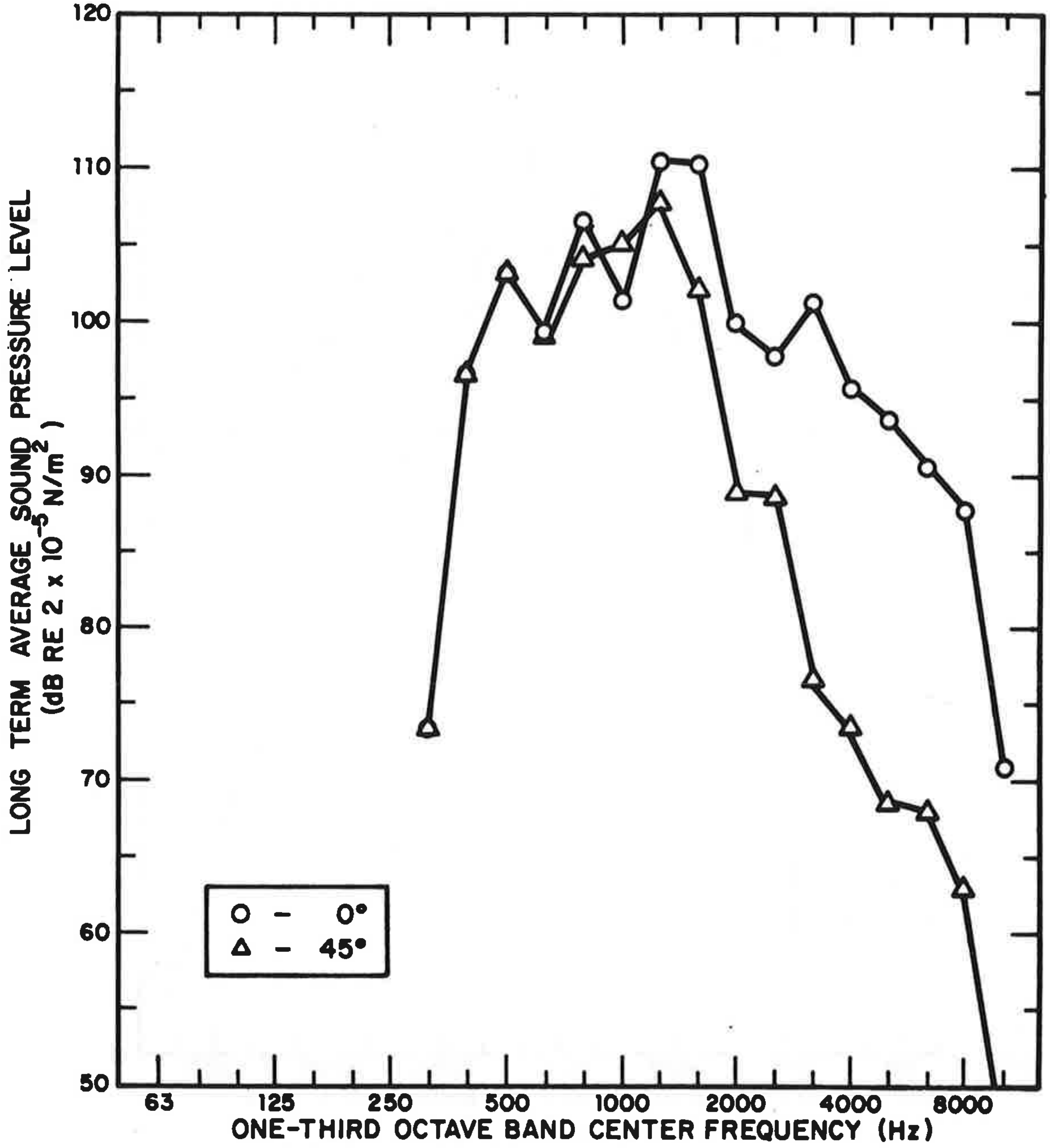


FIG. 7. LEAST-SQUARES FIT TO SOUND-PRESSURE LEVEL SPECTRA OF ALL ELECTRONIC SIRENS — YELP.

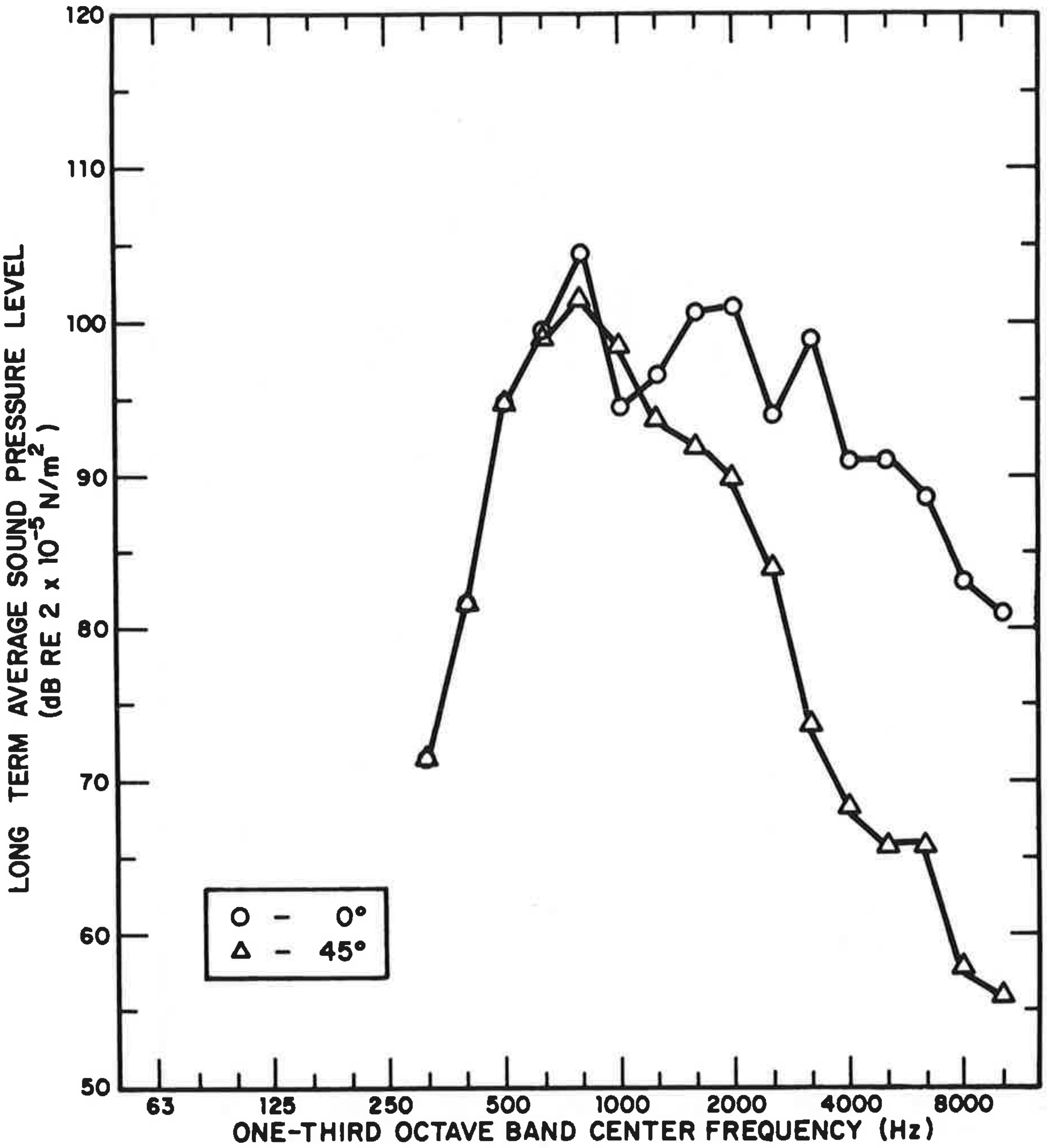


FIG. 8. LEAST-SQUARES FIT TO SOUND-PRESSURE LEVEL SPECTRA OF ALL ELECTRONIC SIRENS — HI-LO.

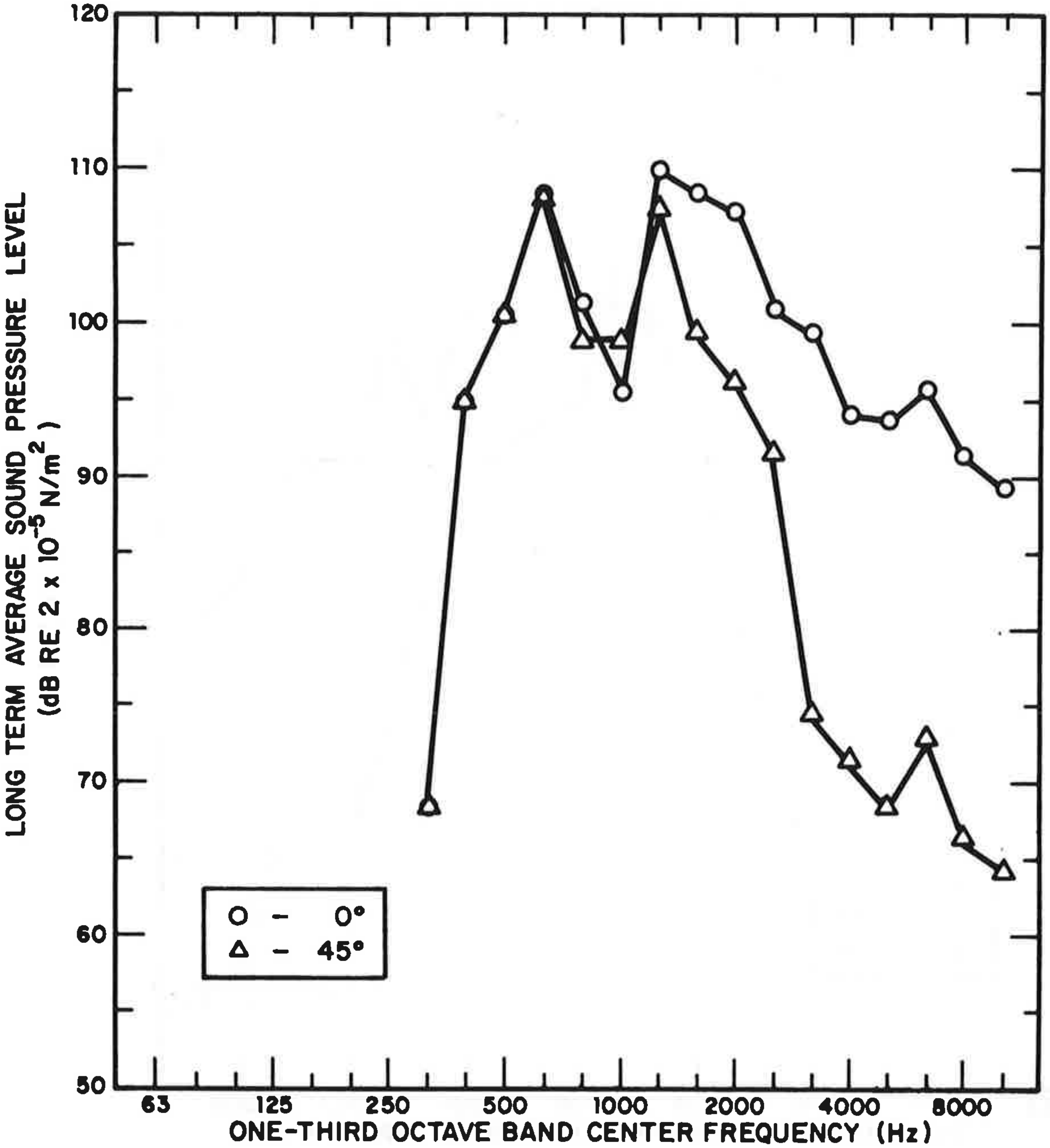


FIG. 9. SOUND PRESSURE LEVEL SPECTRUM OF B&M MODEL S8-M9 SIREN – MECHANICAL.

3. ACOUSTIC INSERTION LOSS OF ROAD VEHICLES

3.1 INTRODUCTION

Sound propagating from the outside to the inside of a vehicle will be affected by its passage through the vehicle structure, and by whether or not the windows and vents are open. Furthermore, the sound level inside the vehicle will be a function of the physical and acoustic properties of the interior space. Thus, for a given external sound field, there are many factors that could affect the sound level heard by a driver: structural details, windows, seals, lagging for vibration and noise reduction, and interior finish.

Because of this complexity, there are no published theoretical analyses relating directly to vehicle insertion loss and very few experimental measurements published in the open literature. Ford Motor Corp. data [5] (obtained during testing to substantiate an advertising claim) show that, on the average, the structure of a large domestic automobile designed to have a quiet interior reduces the noise received inside by 20 dB(A) from the exterior levels.

Presently, the most comprehensive set of insertion loss data is that generated by the National Bureau of Standards in a prior study of sirens [6] for the Department of Justice. These results are given as mean spectrum levels of insertion loss for sound incident on test vehicles from four directions. The NBS tested 23

American-made automobiles with the windows closed.

There were no relevant results for insertion loss of vehicles other than automobiles, nor any examples where the windows of the test vehicles were open. Accordingly, BBN designed an experiment to add to the existing data.

3.2 METHOD

3.2.1 Insertion Loss And Measurement Techniques

Insertion loss was defined as the difference in the sound level observed at the driver's position in a vehicle from that observed at the same location without the vehicle, for the same external noise source.

The insertion loss was determined by establishing a sound field and measuring the sound level at a reference position. A test vehicle was then positioned so that the driver's location was at this reference position. Measuring the sound level with the vehicle present thus produced all the data needed to compute insertion loss.

3.2.2 Test Vehicles, Instrumentation, And Procedure

Six vehicles were studied; 3 used cars, a 20 ft truck with a van body, a school bus, and an ambulance. The vehicles are described in detail in Table 4. It should be noted that all vehicles

TABLE 4. DETAILS OF VEHICLES TESTED.

Vehicle 1 - 1972 Chevrolet Vega Kammback, 2-door, 4 cylinder engine, automatic transmission, 43,000 miles.

Vehicle 2 - 1974 Plymouth Scamp, 2-door, 6 cylinder engine, automatic transmission, power steering, 14,000 miles

Vehicle 3 - 1974 Ford Galaxie 500, 2-door hardtop, 8 cylinder engine, automatic transmission, power steering and brakes, air conditioning, 76,000 miles.

Vehicle 4 - 1973 International Harvester Loadstar 1700 truck, 20 ft, manual gearbox, 28,000 miles.

Vehicle 5 - 1970 International Harvester School Bus, manual gearbox, mileage unknown.

Vehicle 6 - 1974 Dodge Tradesman Ambulance, 8 cylinder engine, automatic transmission power steering and brakes, mileage not noted.

showed normal mileage and wear for their age, except the large Ford automobile, which was a former government pool vehicle and had traveled 76,000 miles in just over two years.

The test area was an empty, level parking lot surrounded by trees and shrubs. The surface was rolled asphalt, and the nearest building was approximately 300 ft (91m) away and to the side of the source-test vehicle centerline. All tests were conducted on summer evenings.

The test sound field was established by using a loudspeaker array, driven by a white-noise source and amplifier (see Fig. 10). The test vehicle was initially absent during calibration of the test site. This calibration involved measurement of the 1/3-octave band spectrum of the sound field at a reference position in front of the loudspeakers and at the head height of the driver in the vehicle to be examined. Table 5 lists the instrumentation used.

The initial test with each vehicle was performed at 0 degrees, with the vehicle facing the loudspeakers and the driver's head at the reference position (Fig. 10). The sound level at the driver position was measured and subtracted from the value without the vehicle present to obtain the insertion loss.

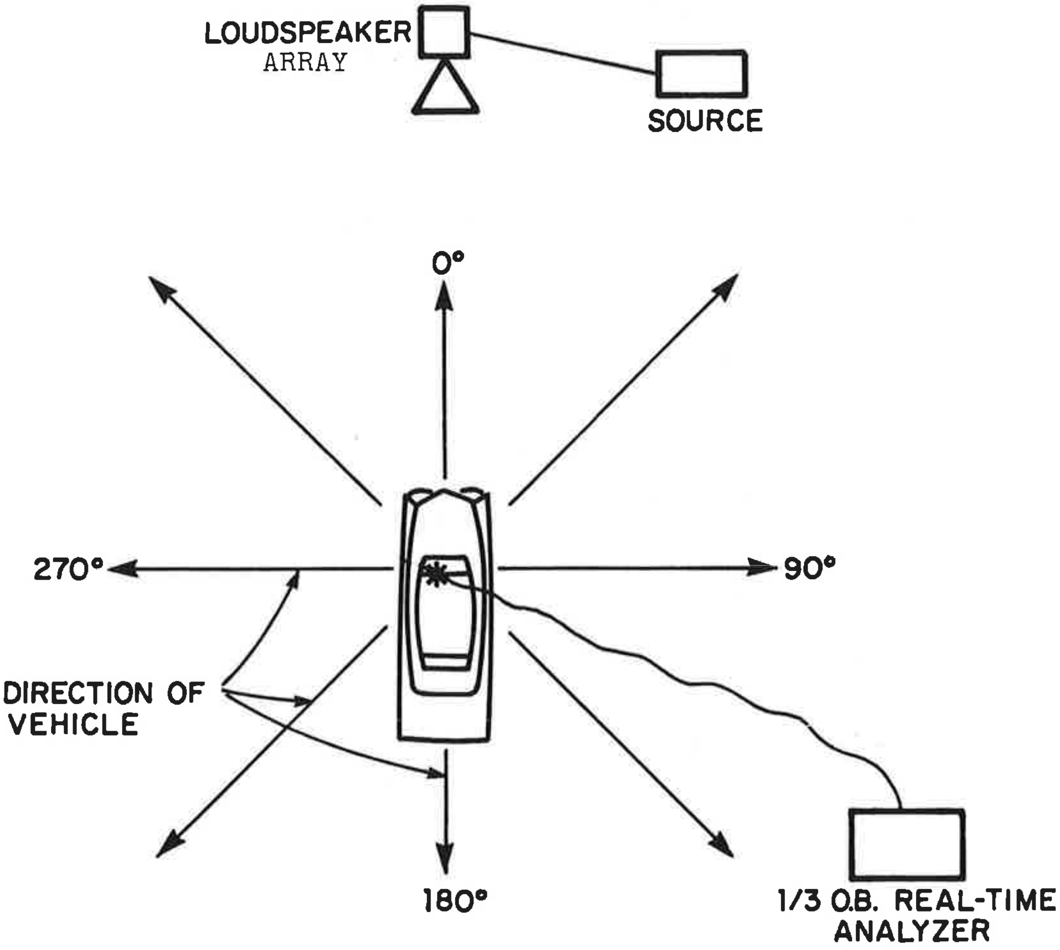


FIG. 10. EXPERIMENTAL ARRANGEMENT FOR INSERTION LOSS MEASUREMENTS.

TABLE 5. INSTRUMENTATION FOR INSERTION LOSS MEASUREMENTS

Source:	Grason-Stadler Model 109B
Loudspeaker:	BBN Full-Range Loudspeaker Assembly
	Altec N-800E Cross-over Network Altec 811 HF horn with 808-16A driver Altec 20802 high intensity low frequency speaker
Microphone:	GR 1/2" Random-Incidence Microphone, Model GR-1962-9601
Analyzer:	Real Time Analyzer composed of:
	GR 1566 Multichannel Amplifier GR 1925 1/3 O.B Multifilter GR 1266 Multichannel RMS Detector Y-Y Plotter

Initial tests were made with all windows tightly closed. They were then repeated with the driver's window open, and then with the passenger-side front window open and the driver's window closed.

The vehicle was then turned 45 degrees and the measurements repeated. In this manner, results were obtained for eight angles of incident sound, each with the three window conditions.

3.3 RESULTS

3.3.1 Comparison With Published Data

The measured insertion losses for the three automobiles tested have been compared with the NBS results for simular models. The cases compared were for 0-degree and 180-degree incidence (sound impinging directly on the front and on the rear of the vehicles) respectively, with the windows closed. The regression line fit to the NBS data closely matches the BBN results for the Chevrolet Vega and for the Ford at frequencies below 1000 Hz. There is some difference in the results on the Plymouth, but this may be due to a model difference.

3.3.2 Effect Of Sound Incidence Angle

The variation in insertion loss with direction of sound incidence was examined for the closed-window case for all three cars. The results are plotted in Figs. 11-13. While these data show some differences (approximately 10 dB) with angle of sound incidence, no general trend is immediately apparent.

It might be expected that gaps in openable windows and door seals would allow more sound to penetrate to the interior than when the sound field is directed at the fixed windshield or rear windows. The results show no significant difference, except perhaps for frequencies of 6300 Hz and above. There is also little difference in insertion loss for sound directed towards the front and towards the back of the automobiles tested. On the basis of these conclusions, it was possible to establish an average insertion loss over all eight incident sound fields, for each window condition.

3.3.3 Effect Of Opening Windows

The effect on the insertion loss of opening the windows of the vehicle is plotted in Figs. 14 and 15. (Relatively little difference was noted between the results with the driver's window open and those with the front-seat passenger's window open.) The figures show the changes in the average insertion loss, obtained by averaging the results for all eight angles of incident sound.

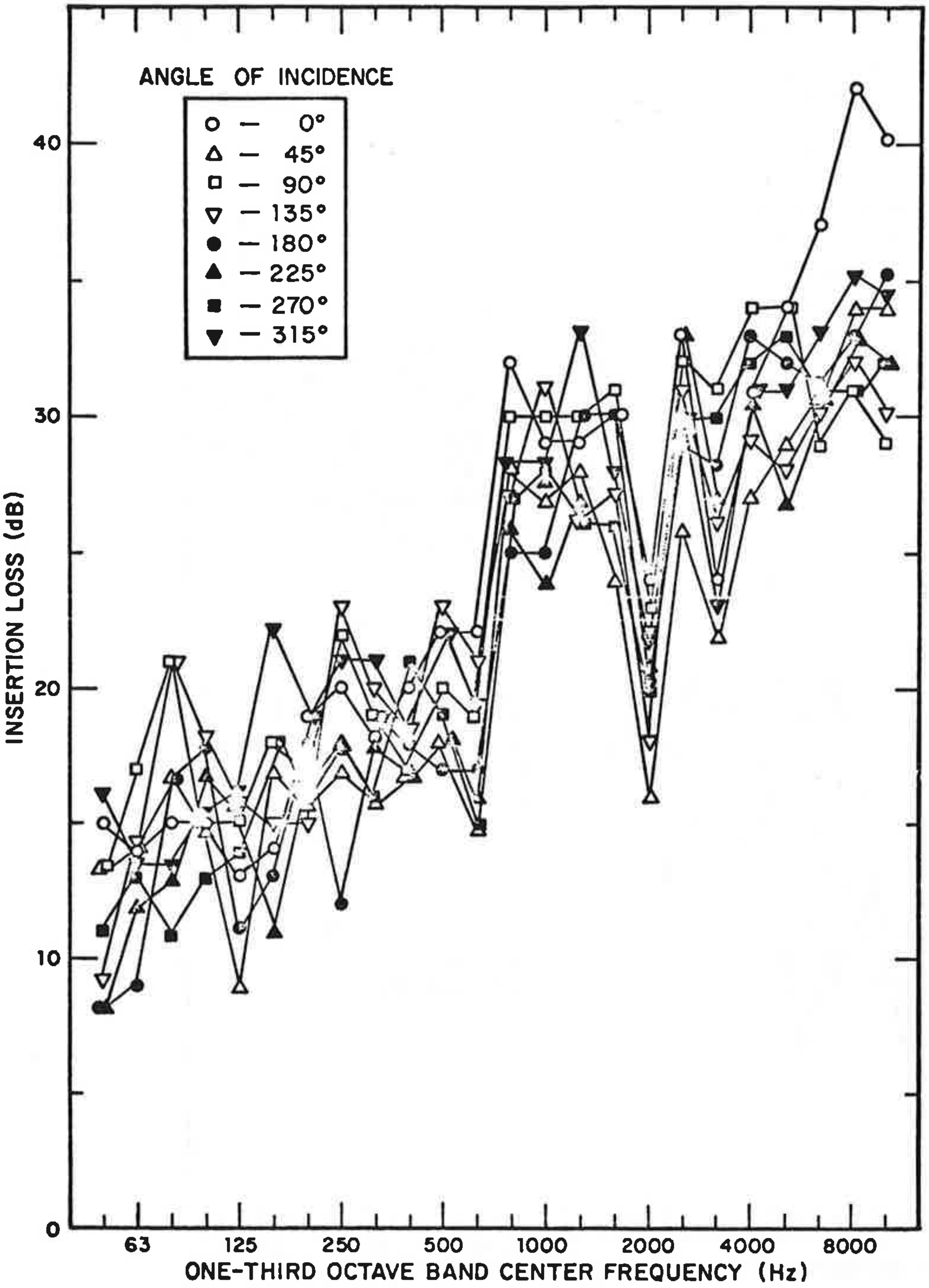


FIG. 11. INSERTION LOSS AS A FUNCTION OF ANGLE OF INCIDENCE OF SOUND: CHEVROLET VEGA, WINDOWS CLOSED.

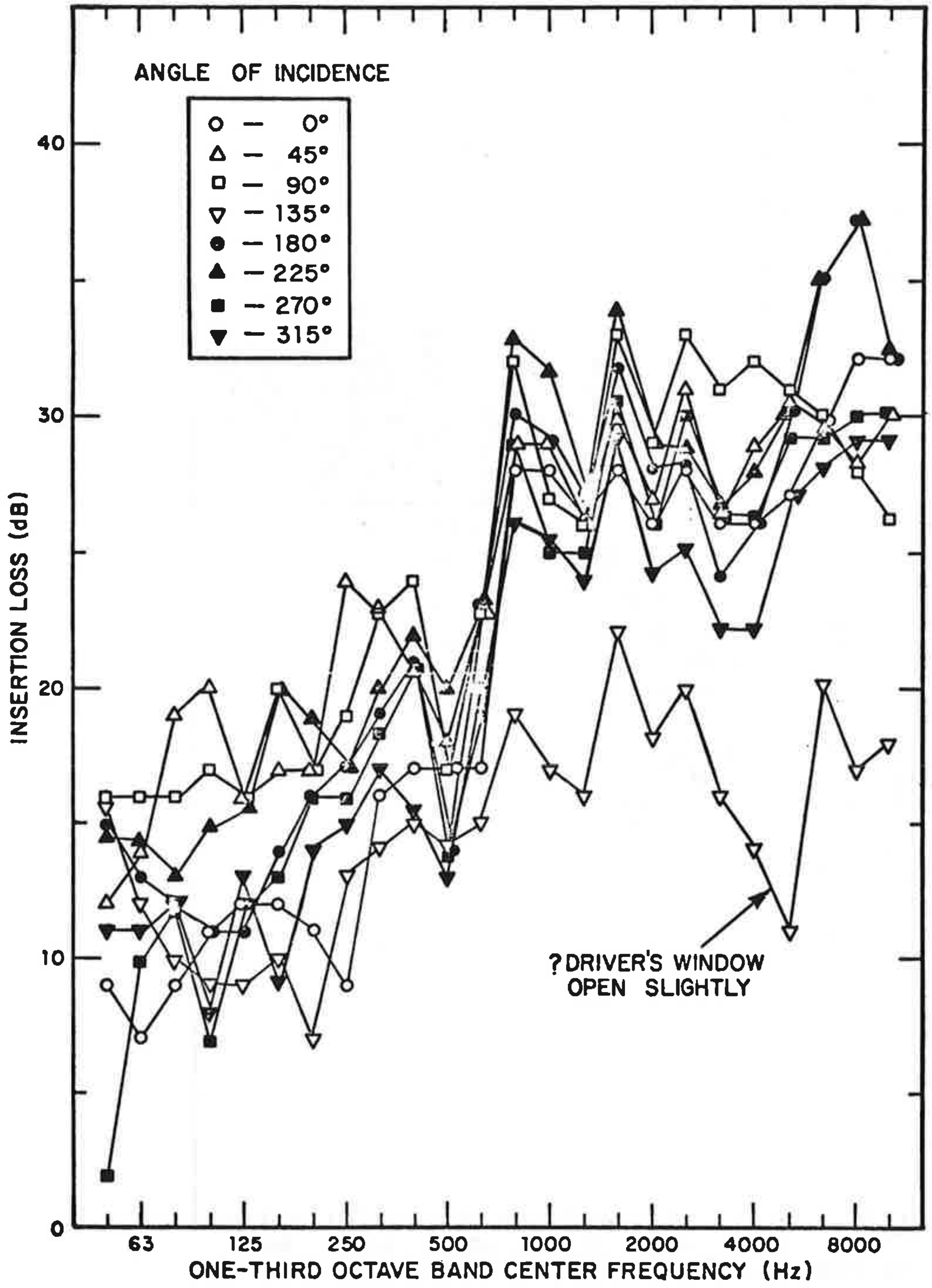


FIG. 12. INSERTION LOSS AS A FUNCTION OF ANGLE OF INCIDENCE OF SOUND: PLYMOUTH SCAMP, WINDOWS CLOSED.

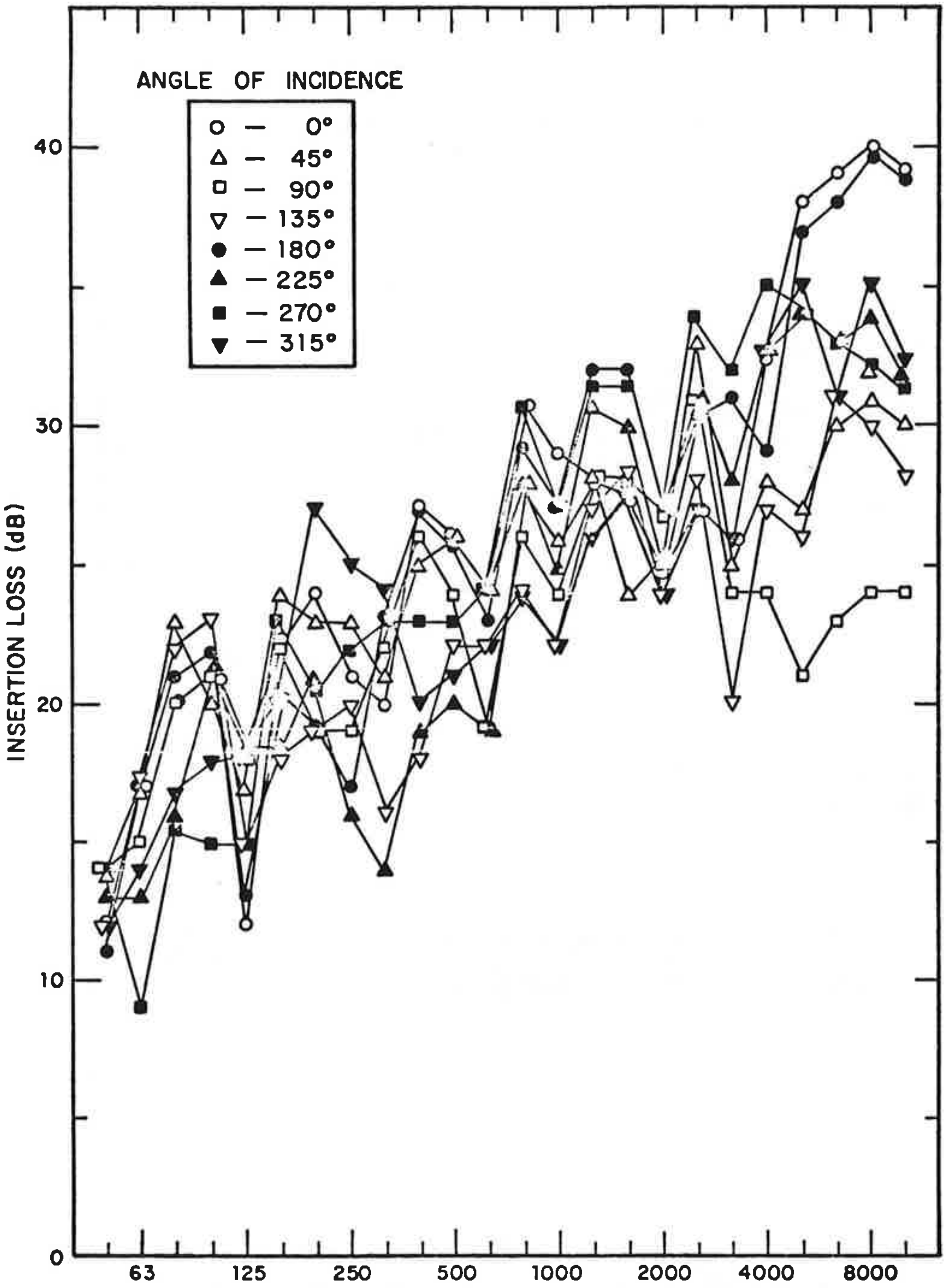


FIG. 13. INSERTION LOSS AS A FUNCTION OF ANGLE OF INCIDENCE OF SOUND: FORD, WINDOWS CLOSED.

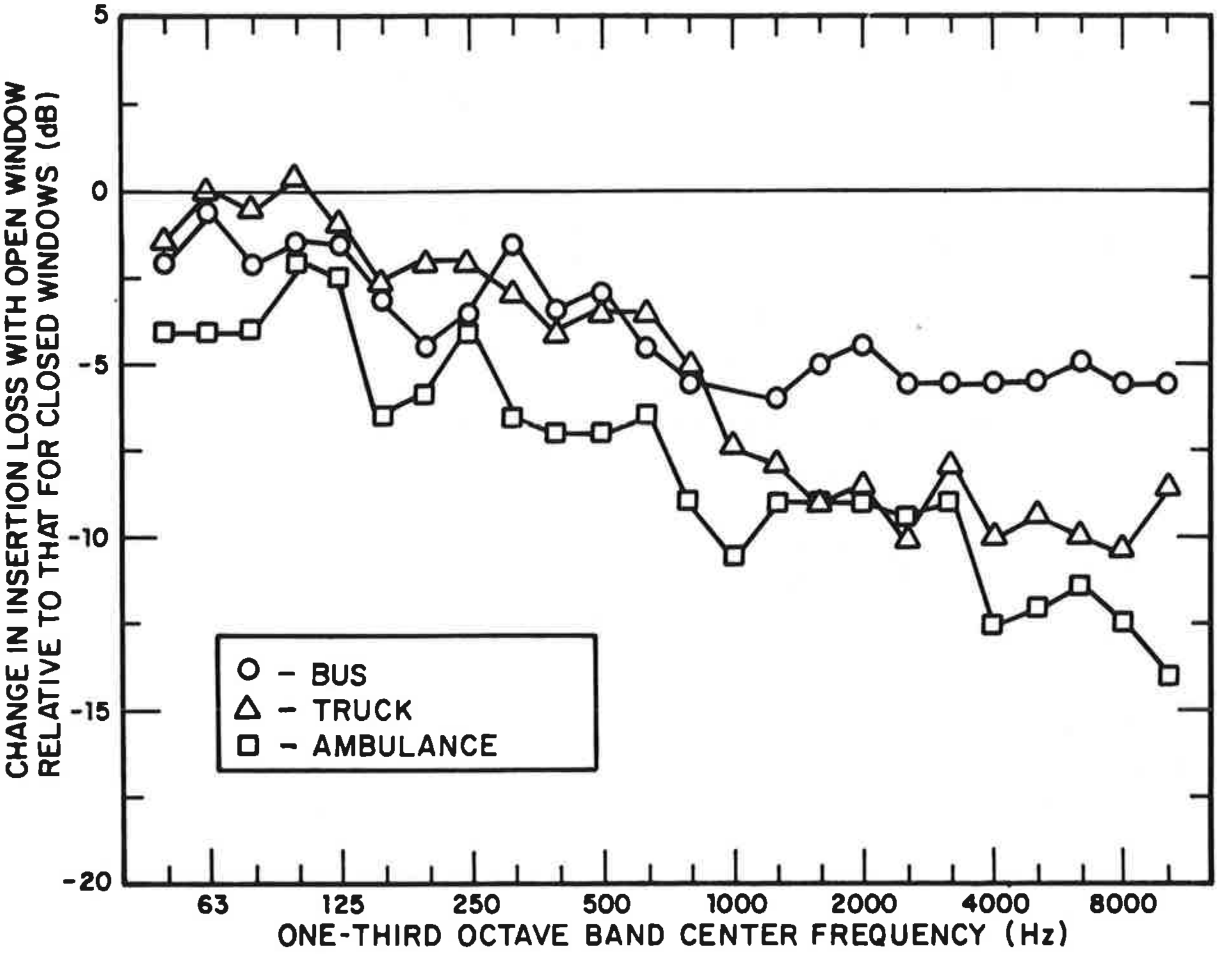


FIG. 14. EFFECT OF AN OPEN FRONT WINDOW ON INSERTION LOSS OF A TRUCK, BUS, AND AMBULANCE.

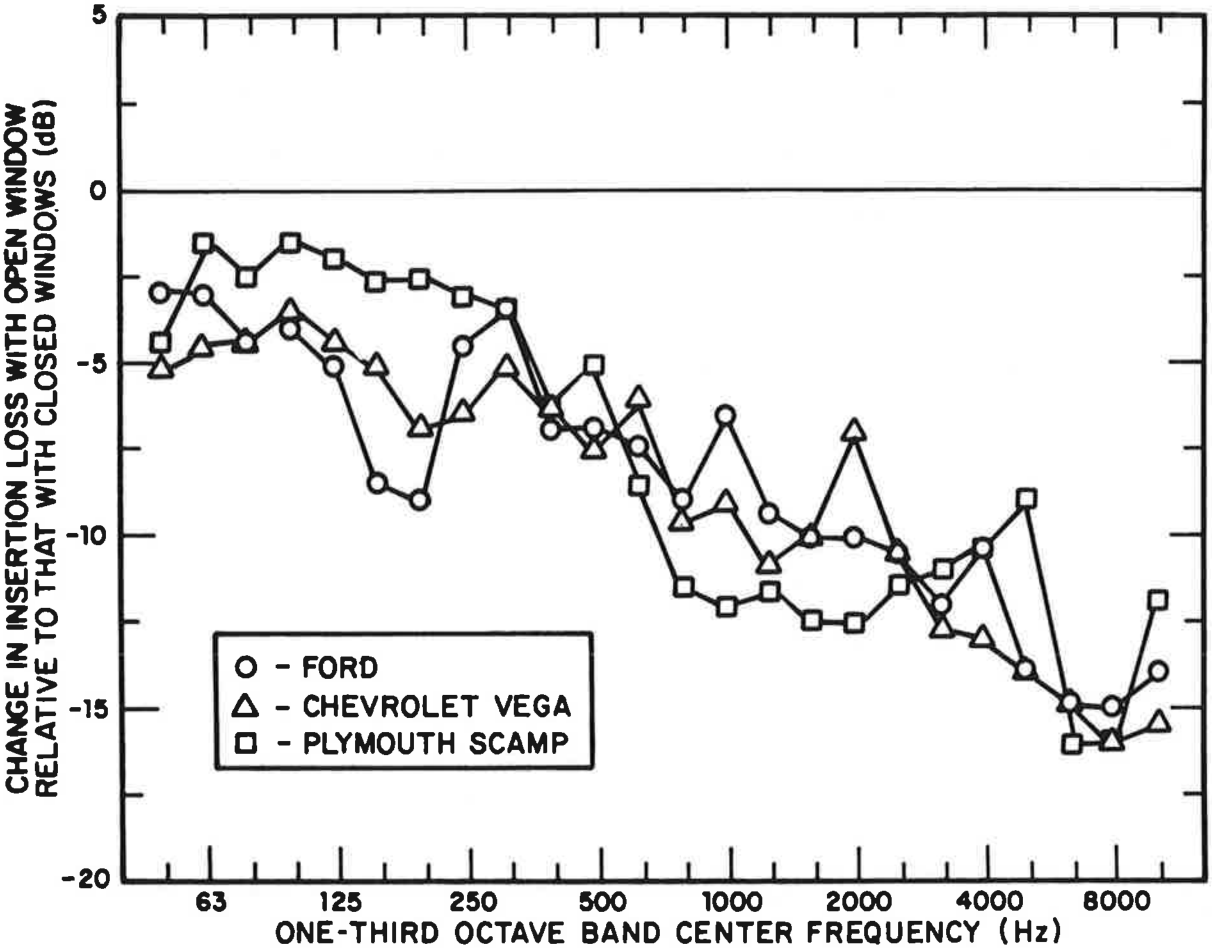


FIG. 15. EFFECT OF AN OPEN FRONT WINDOW ON INSERTION LOSS OF THREE AUTOMOBILES.

The effect of opening the windows is a reduction in the insertion loss, as would be expected, with a greater reduction for the higher frequencies. The results for the bus, Fig. 14, show the least change, probably because in this case only a single window nearest the front of the vehicle was opened on either side. The greatest influence of open windows on insertion loss was observed for the automobiles (Fig. 15).

3.4 REPRESENTATIVE AVERAGE VALUES FOR VEHICLE INSERTION LOSS

Representative average insertion loss spectra were developed for use in the study based on the mean results obtained for the three automobiles for all eight incident sounds. It is reasonable to use these representative average values for prediction of AWD effectiveness because:

1. The measured insertion losses were greatest for automobiles
2. The sounds of an emergency vehicle can come from any angle in the horizontal plane.

Figures 11-13 show the measured insertion loss for the three automobiles with windows closed. The results for each vehicle at each frequency were averaged, and these three means were averaged again to produce the curves shown in Fig. 16. These are the representative average closed-window spectra used in the following sections of this report. The change in insertion loss

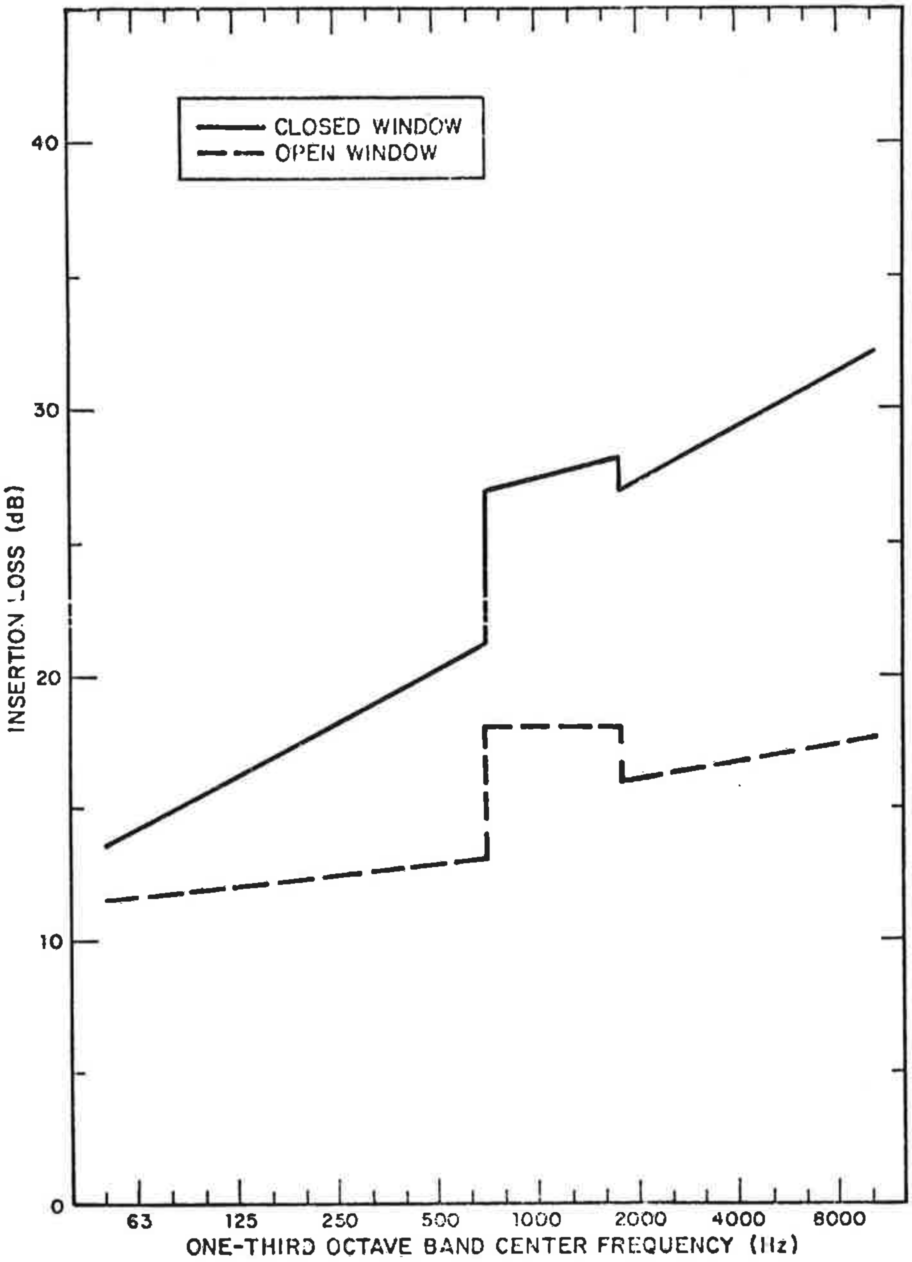


FIG. 16. REPRESENTATIVE AVERAGE VALUES FOR INSERTION LOSS OF AUTOMOBILES.

for the same three vehicles due to an open window (Fig. 15) were averaged and subtracted from the closed-window spectrum to obtain the spectrum for windows open, also shown in Fig. 16.

4. INTERIOR NOISE AND ROAD VEHICLES

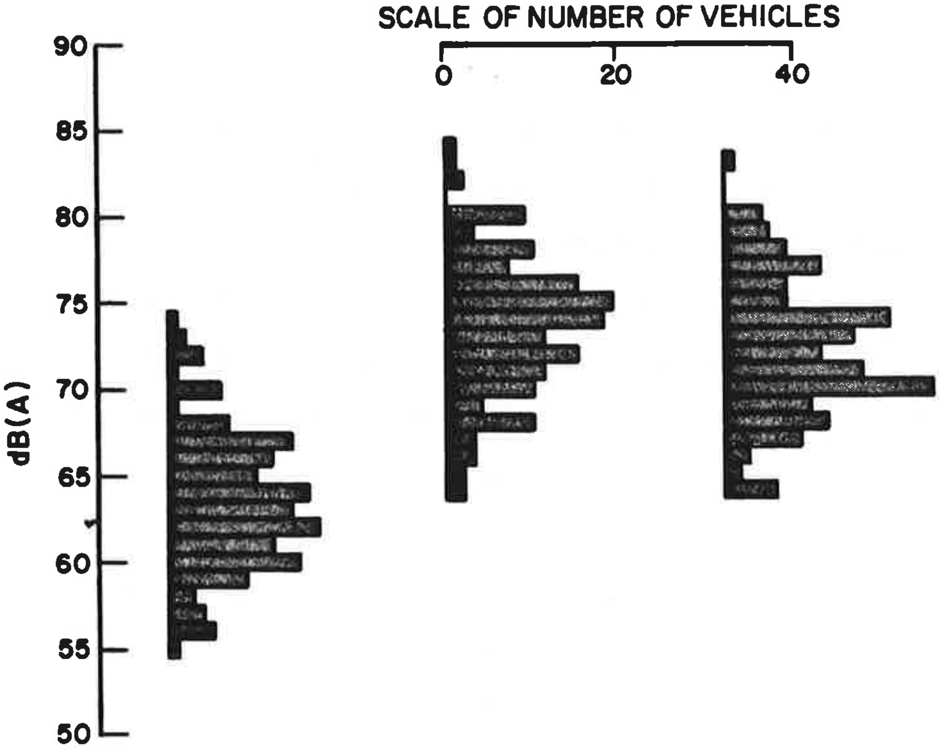
4.1 INTRODUCTION

The interior noise of a vehicle can mask the sound of a siren, and this masking decreases the chance for a driver to recognize the presence of the emergency vehicle. The sources of interior noise include road and tire interaction, aerodynamic flow over the vehicle, and the vehicle's mechanical drive train, exhaust, and accessories. The magnitude of the noise level will depend upon structural details of the vehicle, the configuration (including whether the windows are open or closed, and which accessories are operating), speed, road conditions and tire type, and the way the vehicle is functioning. Because of the wide variation in these parameters for all vehicles on the road, there is a correspondingly wide range of interior noise levels. The purpose of the experiments conducted here was to define certain average values of interior noise level.

Popular Science [7] reports the interior A-weighted noise level at the driver's ear for over 150 domestic and foreign automobiles for three different operating surface conditions. Figure 17 shows these results. The standard deviation for each set of data is about 4 dB for each condition. The U.S. Environmental Protection

4 dB for each condition. The U.S. Environmental Protection

Agency has determined, chiefly on the bais of these results, that the typical cruising noise levels inside automobiles range from 62 to 83 dB(A) with an energy mean of 74 dB(A) [8].



	30 mph Smooth Road	30 mph Rough Road	60 mph Smooth Road
Mean	63.4	73.5	72.0
Standard Deviation	4.05	4.32	3.97

FIG. 17. INTERIOR NOISE OF AUTOMOBILES, FROM POPULAR SCIENCE [7].

Detailed tests of interior noise levels have been reported by the National Bureau of Standards for the 23 almost-new American automobiles mentioned in Sec. 3 [6]. Mean results for interior noise spectra were given for a series of tests involving four different operating conditions, both with and without the air conditioner operating.

Opening vehicle windows is known to increase buffeting and low-frequency noise [9], and also to allow exhaust, road, and tire noise to increase inside the vehicle.

Another factor that can affect the interior noise level is the use of studded or snow tires [10], which can add as much as 8 dB to interior noise. Differences in road surface can cause an increase of up to 10 dB [7], while a wet road can add 3 dB to the noise [10].

The spectrum of vehicle interior noise is broadband, and falls rapidly with increasing frequency [6, 9, 11, 12, 13, 14].

Speed-dependent noise sources include aerodynamic noise and tire-road interaction noise. Both of these sources cause the noise generated to increase at a rate of 12 dB per doubling of speed, according to theory [10, 15]. On the other hand, engine/drive-train noise is expected to increase at the rate of 6 dB per doubling of vehicle speed, for the noise generated outside of the passenger compartment. The increase in the interior noise level measured for a doubling of speed is reported as 7.5 dB, 8.6 dB, and 10 dB [11, 7, 9]. These results cover a wide range of imported, European, and domestic automobiles and thus, effectively, a varying combination of the speed-dependent sources. The data suggest that in some of the smaller and less expensive vehicles, the engine/drive-train noise dominates. For larger cars with more mechanical isolation, the influence of tire and aerodynamic noise can be more significant, causing an apparently greater rate of increase of noise with speed.

The interior noise of trucks [16-21] is, in general, greatly influenced by engine/drive-train sources; the gearbox and exhaust noise can produce a spectrum shape containing more discrete tones than that for automobiles.

Most of the published data on interior noise levels of road vehicles are for automobiles, and most of these results are for new or nearly new vehicles, operating at a steady speed with all the windows shut tight and with no accessories operating, other than perhaps the heating/air conditioning fan. This cannot be considered as typical of the operating conditions of vehicles on roads in the U.S.A. because it does not include configurations that can produce extremes of interior noise levels. The influence of open windows, with the increased aerodynamic noise and the sounds of other traffic, can be important. The radio is also a key element in controlling interior noise levels of vehicles, since it is normally adjusted to be audible over all the other sounds. Therefore, the radio probably causes the highest interior noise levels against which the siren must compete.

The measurements reported here were designed to examine all of these factors in order to produce representative levels of the interior noise in vehicles on the road today.

4.2 TEST PROCEDURE

The six different vehicles examined were the same six vehicles used for the insertion loss measurements (see Sec. 3 and Table 4).

The sound levels at the driver's right ear were measured and a recording was made (for later analysis) while the six vehicles were operated at:

-> A steady 55 mph on the open road;
-> A steady 30 mph on the open road;
-> Varying speeds in an urban situation.

For each of these three cases, the sound levels were noted for the following conditions:

-> All windows tightly shut;
-> The driver's window down, with all others shut

-> The passenger's window down, with all the others shut

-> The radio set for "rock-n-roll" music.*

The instrumentation used is listed in Table 6.

Tape-recorded data were reproduced through a 1/3-octave band real-time spectral analyzer. Using an eight second averaging time, the A-weighted sound levels were determined from the 1/3-octave band values.

A windscreen was used on the microphone to avoid any induced wind effect when the window was open.

An exception to the program outlined above was that the measurements in the urban traffic situation were made with either all windows up or all windows down in order to examine the influence of noise from other traffic. The analysis of this urban noise was done with a shorter (1/2-sec) integrating time. The results were then presented as the maximum and minimum values recorded during each 5-min test period.

The measurements on the ambulance included additional tests with the vehicle communication radios in operation and with the electronic emergency siren operating.

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*In this case the radio volume was set by the driver at what he considered to be an acceptable level.

TABLE 6. INSTRUMENTATION FOR INTERIOR NOISE MEASUREMENTS

Sound Level Meter: GR Type 1933 Precision Sound-Level Meter and Analyzer, Serial Number 796

Microphone: GR 1/2" Random Incidence Microphone, Model: GR-1962-9601, Serial Number 980.

Calibrator: GR Type 1562-A Sound-Level Calibrator, Serial Number 7910.

Recorder: Kudelski Nagra IV Recorder.

Analyzer: Real Time Analyzer composed of:

GR 1566 Multichannel Amplifier
GR 1925 1/3 O.B. Multifilter
GR 1266 Multichannel RMS Detector
X-Y Plotter

4.3 RESULTS

4.3.1 Comparison With Published Data

The results for the three automobiles were compared with the NBS results [6]. The Vega station wagon measured during this study was much noisier than the sedan measured by NBS, and it was subjectively observed that the mechanical noise was very obtrusive at higher speeds. A peak in the 100-Hz 1/3-octave band at 55 mph was strong enough to dominate the A-weighted level, despite the deemphasis of the levels at this frequency by the weighting network.

The measured levels of interior noise in the Plymouth and Ford showed good agreement with the NBS results.

A comparison of the current measurement within a single, 2-axle truck with the results reported by DOT [17] for tractor units gave close agreement despite the difference in vehicles.

4.3.2 Comparison Of All Six Vehicles Tested

Figures 18-21 show the measured interior sound level spectra at 55 mph for all six vehicles tested, for various window and radio conditions. These results illustrate the wide scatter for this limited selection of vehicles.

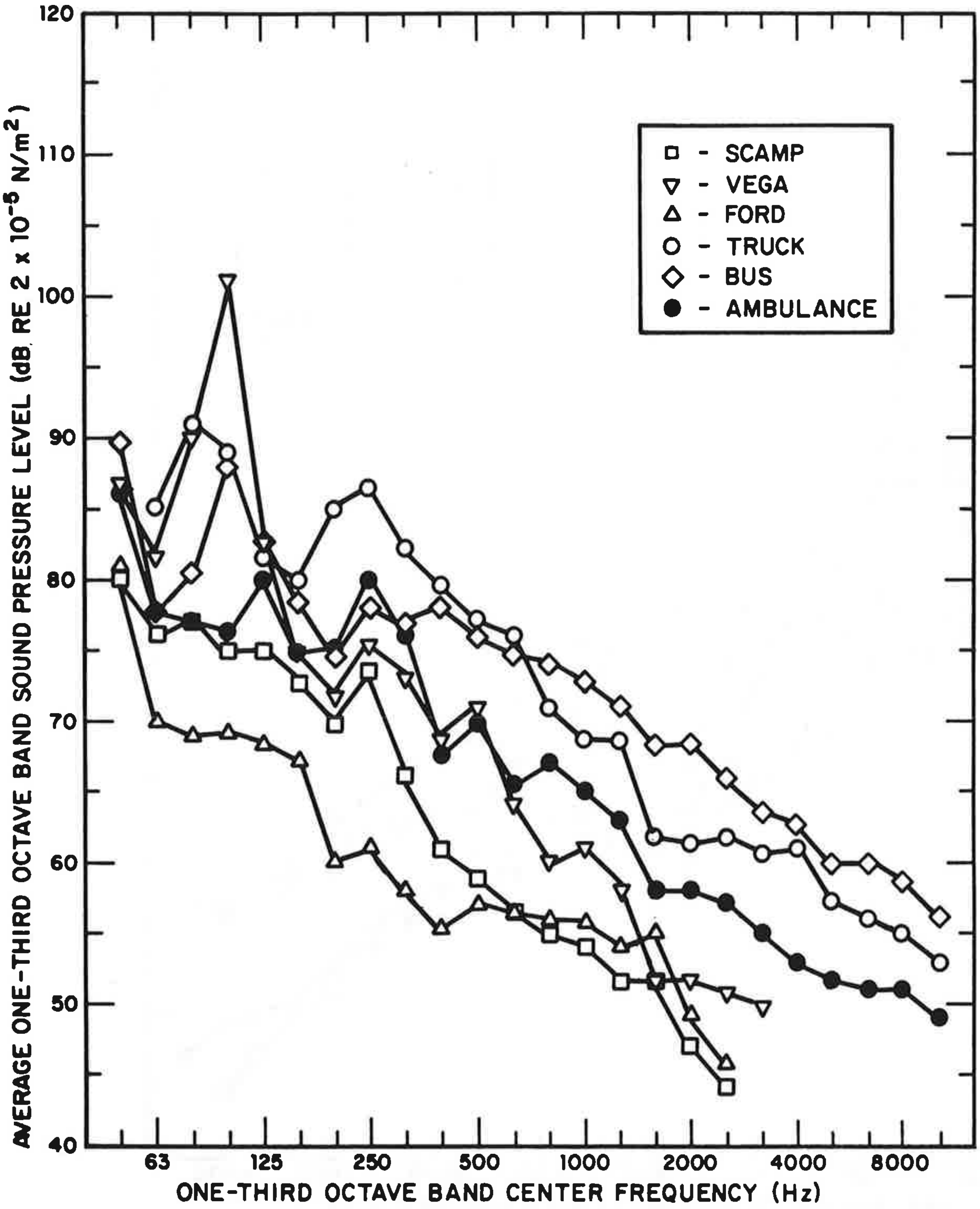

FIG. 18. INTERIOR SOUND LEVELS WITH WINDOWS CLOSED, 55 MPH.

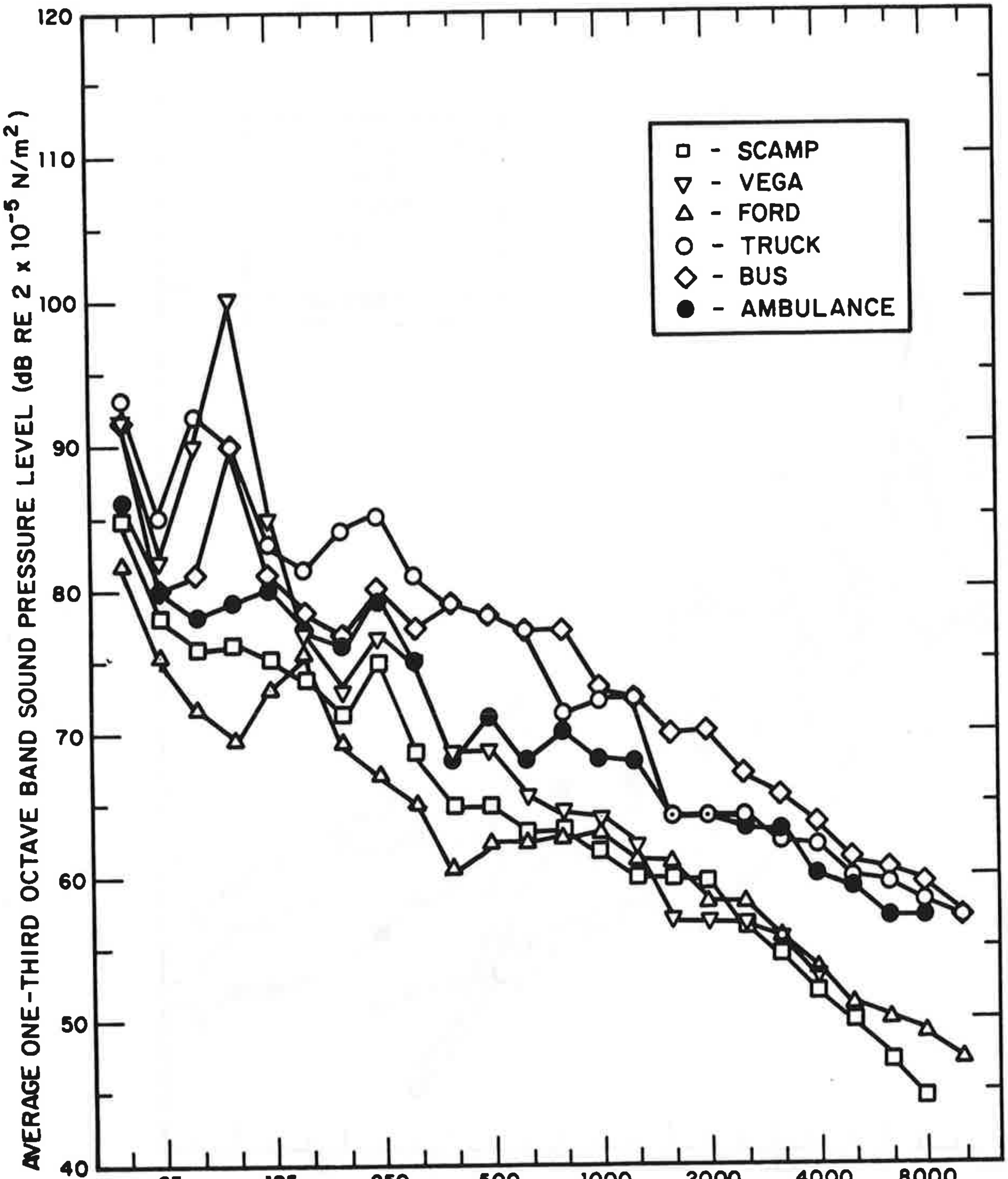

FIG. 19. INTERIOR SOUND LEVELS WITH DRIVER'S WINDOW OPEN, 55 MPH.

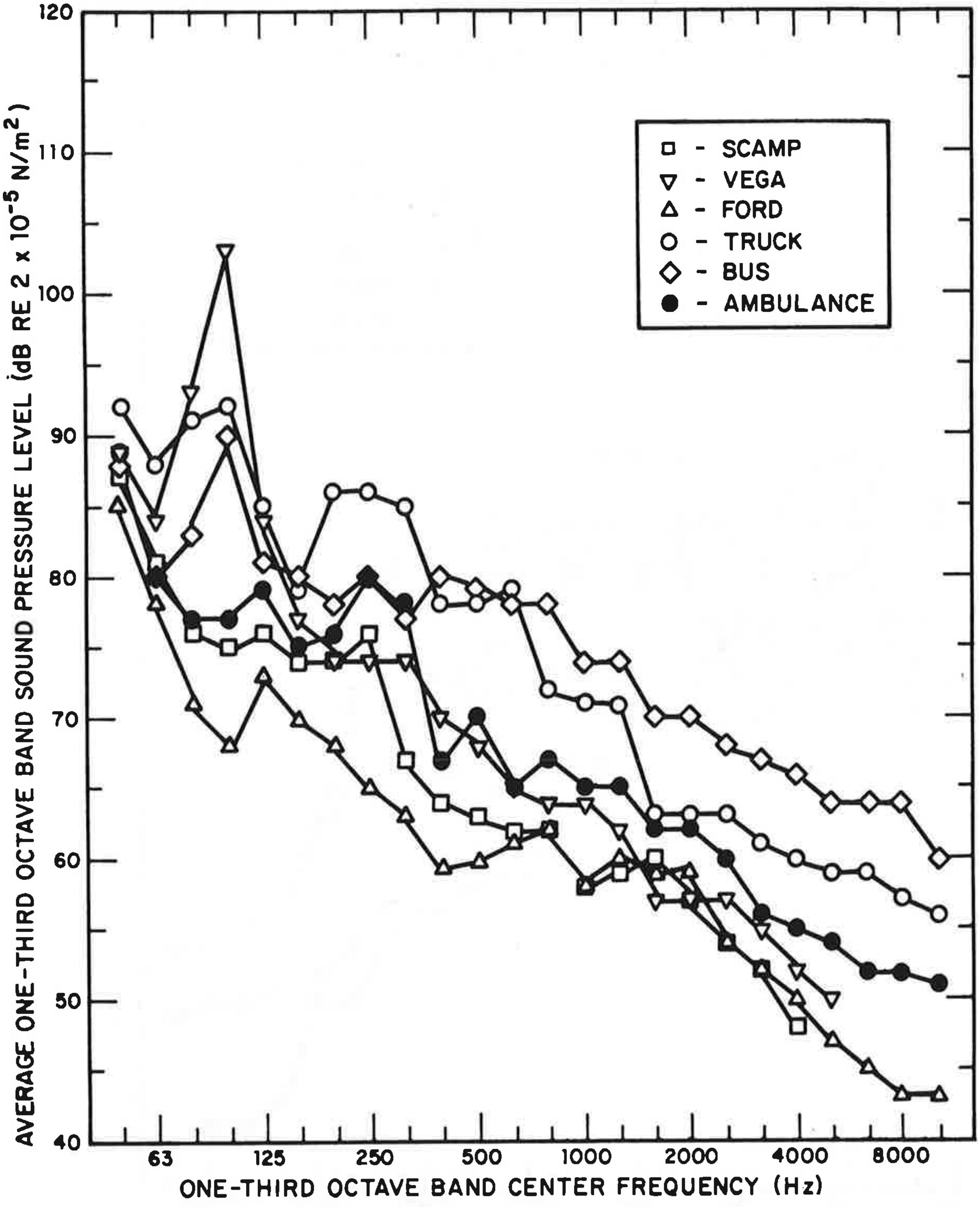

FIG. 20. INTERIOR SOUND LEVELS WITH PASSENGER WINDOW OPEN, 55MPH.

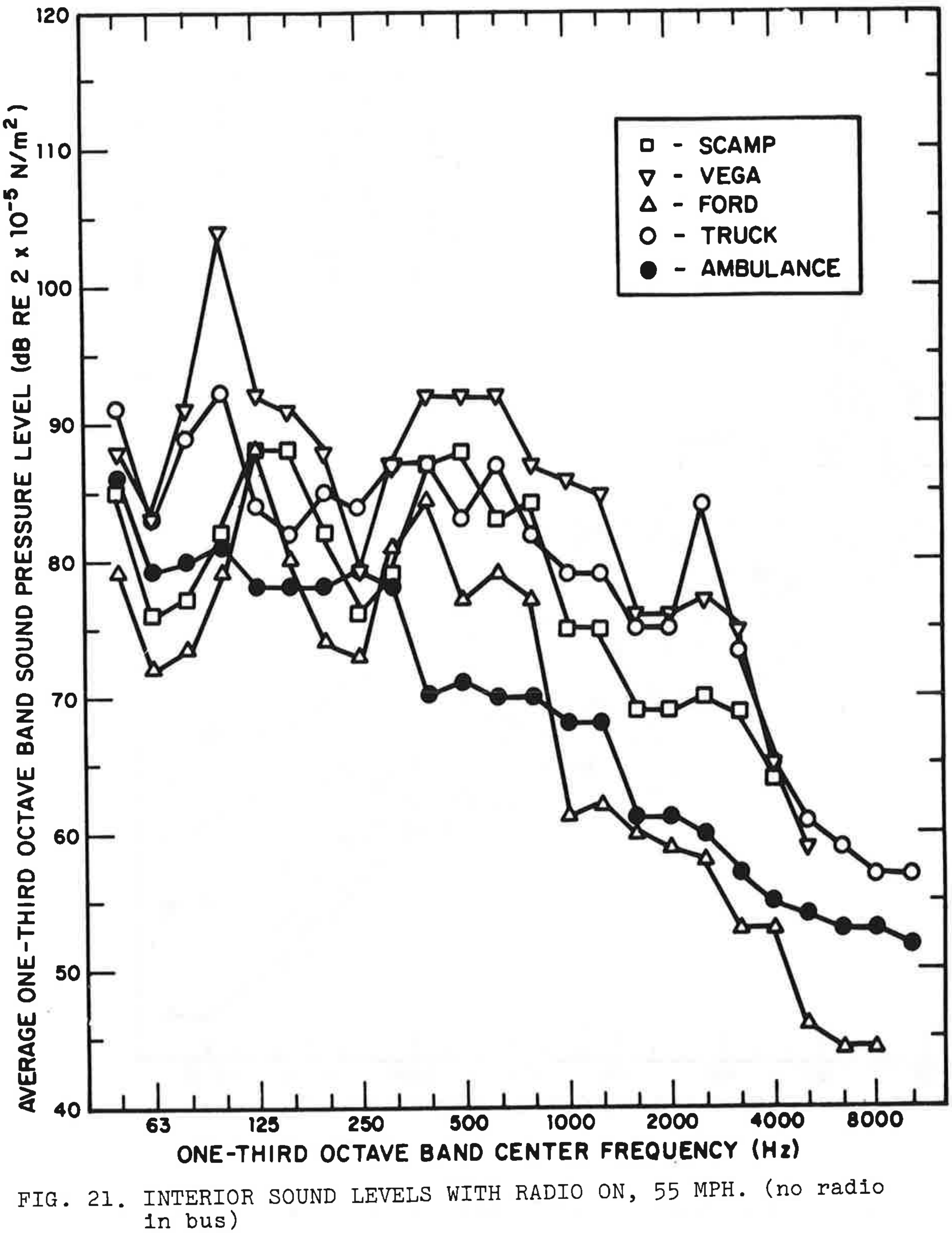

FIG. 21. INTERIOR SOUND LEVELS WITH RADIO ON, 55 MPH. (no radio in bus)

4.3.3 Urban Noise Measurements

The urban noise measurements (with all windows open) showed wide range in sound level. The noisiest conditions observed for any length of time occurred when the test vehicle was stationary alongside an idling truck at a traffic light. However, even this sound level increased momentarily as the truck accelerated. The maximum level observed was an "A-weighted" sound level of 84 dB(A).

4.3.4 Effect of Speed

For all vehicles, a marked increase in sound level was observed as speed increased from 30 to 55 mph, but the amount of increase varied with the vehicle. The Vega showed the greatest increase in interior noise of all the autos, with windows closed. With windows open, the Ford and Plymouth showed the greater increase in sound level with speed.

Table 7 gives the A-weighted sound levels for the three automobiles with windows closed at the two test speeds, the difference between these levels, and the corresponding increase for a doubling of speed.

TABLE 7. A-WEIGHTED INTERIOR NOISE LEVELS.

	Windows Closed, "A-weighted" Levels			
	55 mph dB(A)	30 mph dB(A)	Diff. (dB)	Diff./Doubling of Speed (dB)
Ford	67	58	9	9.7
Plymouth	69	65	4	4.4
Vega	84	68	16	17.5
Truck	86	75	11	12.0

4.3.5 Effect of Opening The Windows

The 1/3-octave band sound pressure spectra for the three autos were examined to determine the effect of opening the windows at the two test speeds. Table 8 shows the A-weighted sound levels for the closed- and open-window tests, and the increases resulting from opening the windows. There is a general increase of 5 dB for the Chevrolet Vega at the 30-mph speed, with a similar increase observed for the Ford and Plymouth at 55 mph.

The increase in 1/3-octave band levels for all vehicles and all configurations due to opening a window was averaged and the results plotted (Fig. 22). The mean values and standard deviations of the results are shown.

4.3.6 Effect Of Radios

The noise spectra for the five vehicles tested with radios (Fig. 21) show a wide scatter. However, it was postulated that the increase in interior noise level when a radio is turned on might be a constant, since the driver would probably set the radio to overcome the otherwise existing ambient interior noise levels. Figure 23 shows the average increase in 1/3-octave band levels observed in the three automobiles, at both speeds, when the radios were on. The mean and standard deviation of the results are shown. Although the scatter is considerable, these results reveal that the increase in the interior masking noise

TABLE 8. INTERIOR A-WEIGHTED LEVELS FOR CARS: EFFECT OF OPEN WINDOWS.

Car	30 mph				
	Windows Closed dB(A)	Driver Window Open dB(A)	Increase in Level dB	Passenger Window Open dB(A)	Increase in Level dB
Vega	68	74	6	73	5
Plymouth	65	67	2	67	2
Ford	58	59	1	60	2

Car	50 mph				
	Windows Closed dB(A)	Driver Window Open dB(A)	Increase in Level dB	Passenger Window Open dB(A)	Increase in Level dB
Vega	84	85	1	87	3
Plymouth	69	74	5	74	5
Ford	67	71	4	71	4

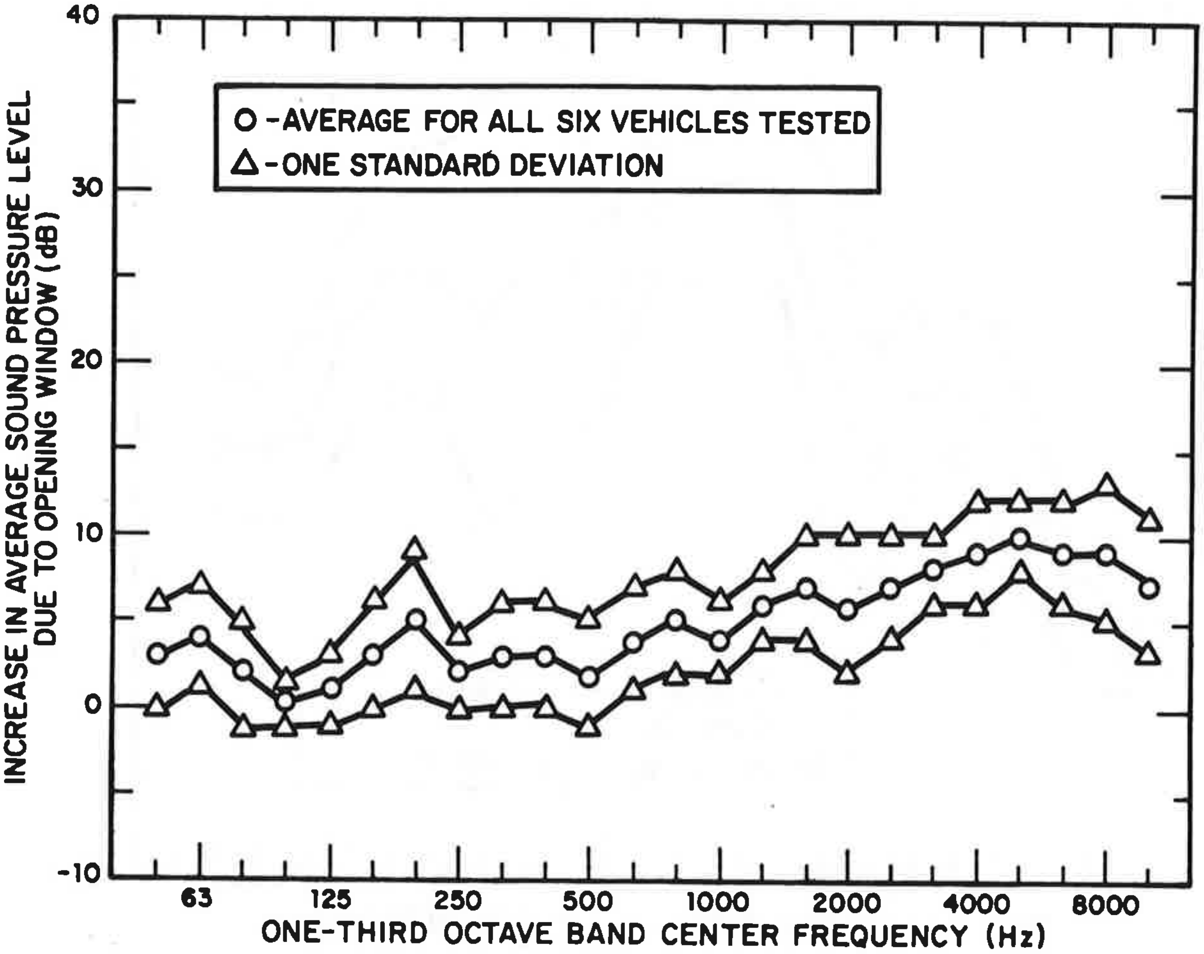

FIG. 22. INCREASE IN LONG-TERM AVERAGE INTERIOR NOISE LEVEL DUE TO OPENING WINDOWS.

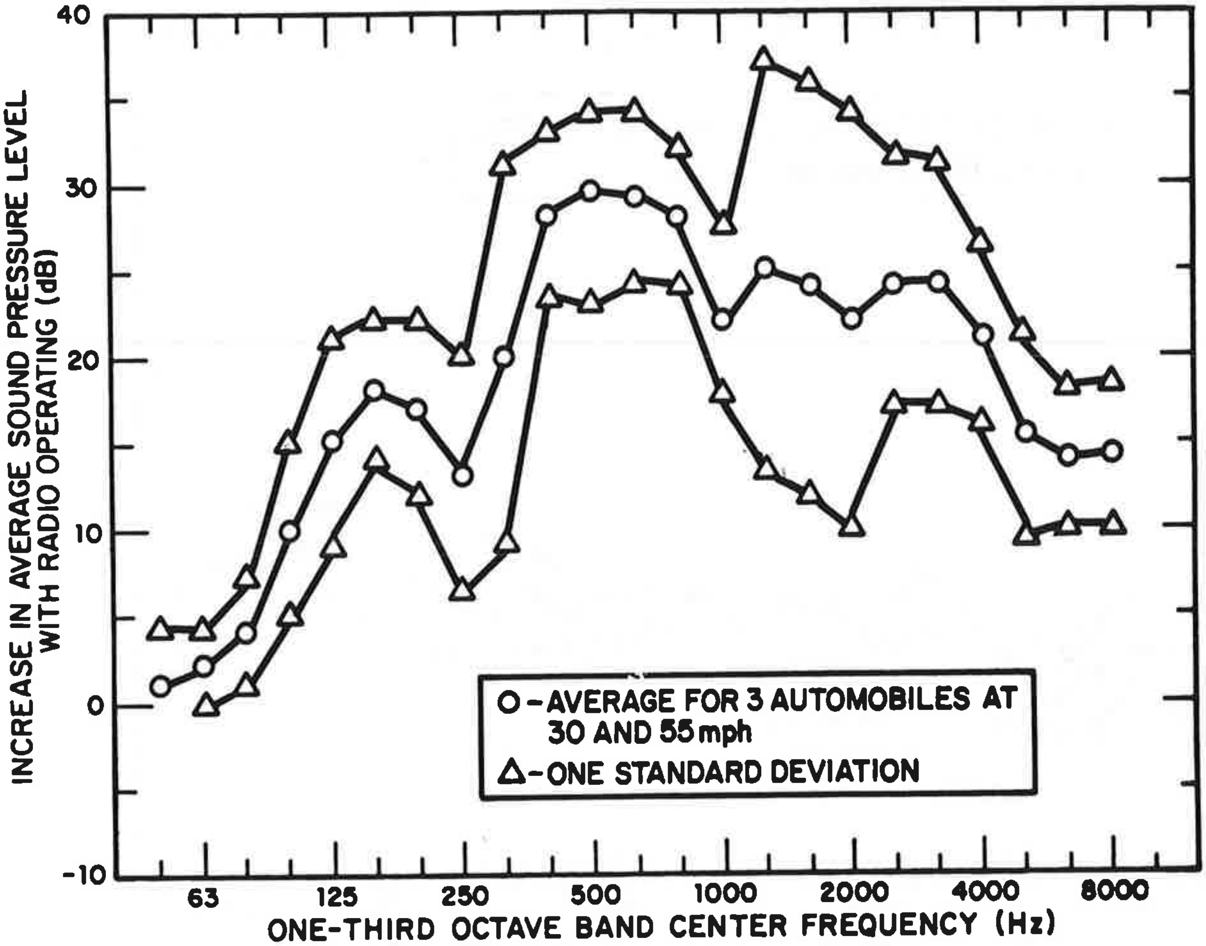

FIG. 23. AVERAGE INCREASE IN LONG-TERM AVERAGE INTERIOR NOISE LEVEL WITH RADIO OPERATING, RELATIVE TO THAT WITH RADIO OFF.

level is greatest in the frequency range from 250 to 2000 Hz, the range within which most sirens normally operate.

4.4 REPRESENTATIVE AVERAGE VALUES FOR INTERIOR NOISE LEVELS

Figure 24 shows the averages of the interior noise level spectra at 55 mph for the three cars and the three commercial vehicles, with windows closed. These values are based on the spectra in Fig. 18. A mean straight-line fit to the two curves is shown. In a similar way, mean straight lines were fitted for the other window and speed conditions.

The interior noise levels are higher when the radio is operating. Figure 25 shows average curves for the three automobiles, the truck, and the ambulance, at 30 and 55 mph with the radio on. (The higher sound level at 30 mph for the truck-ambulance average is caused by communication-radio noise in the ambulance.) The proposed idealized result shown fits the most representative values; it corresponds to an A-weighted level of 88 dB(A). Although this may seem high, it is only 13 dB above the average interior noise at 55 mph with window closed.

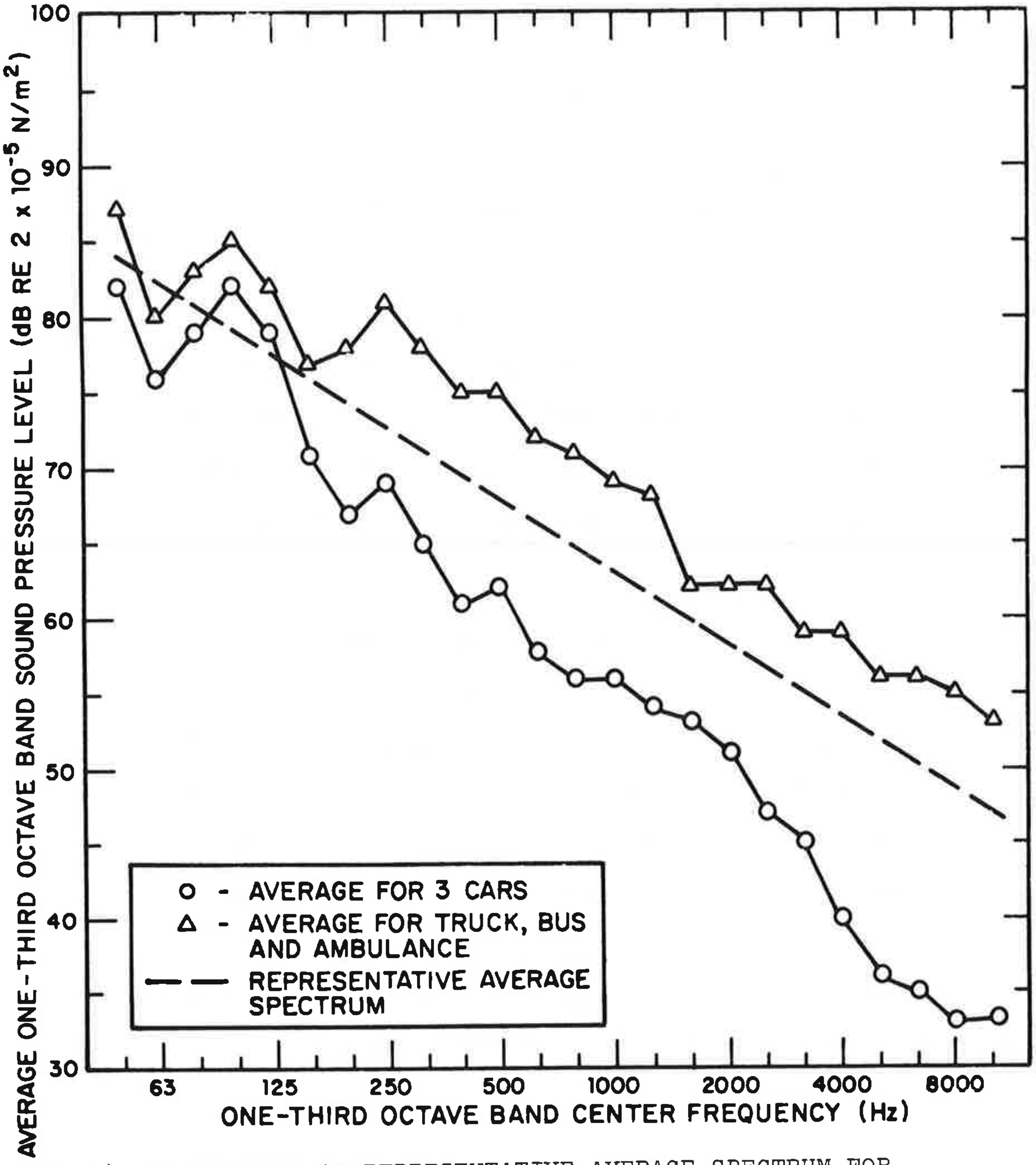

FIG. 24. DERIVATION OF REPRESENTATIVE AVERAGE SPECTRUM FOR INTERIOR NOISE LEVEL; WINDOWS CLOSED, 55 MPH.

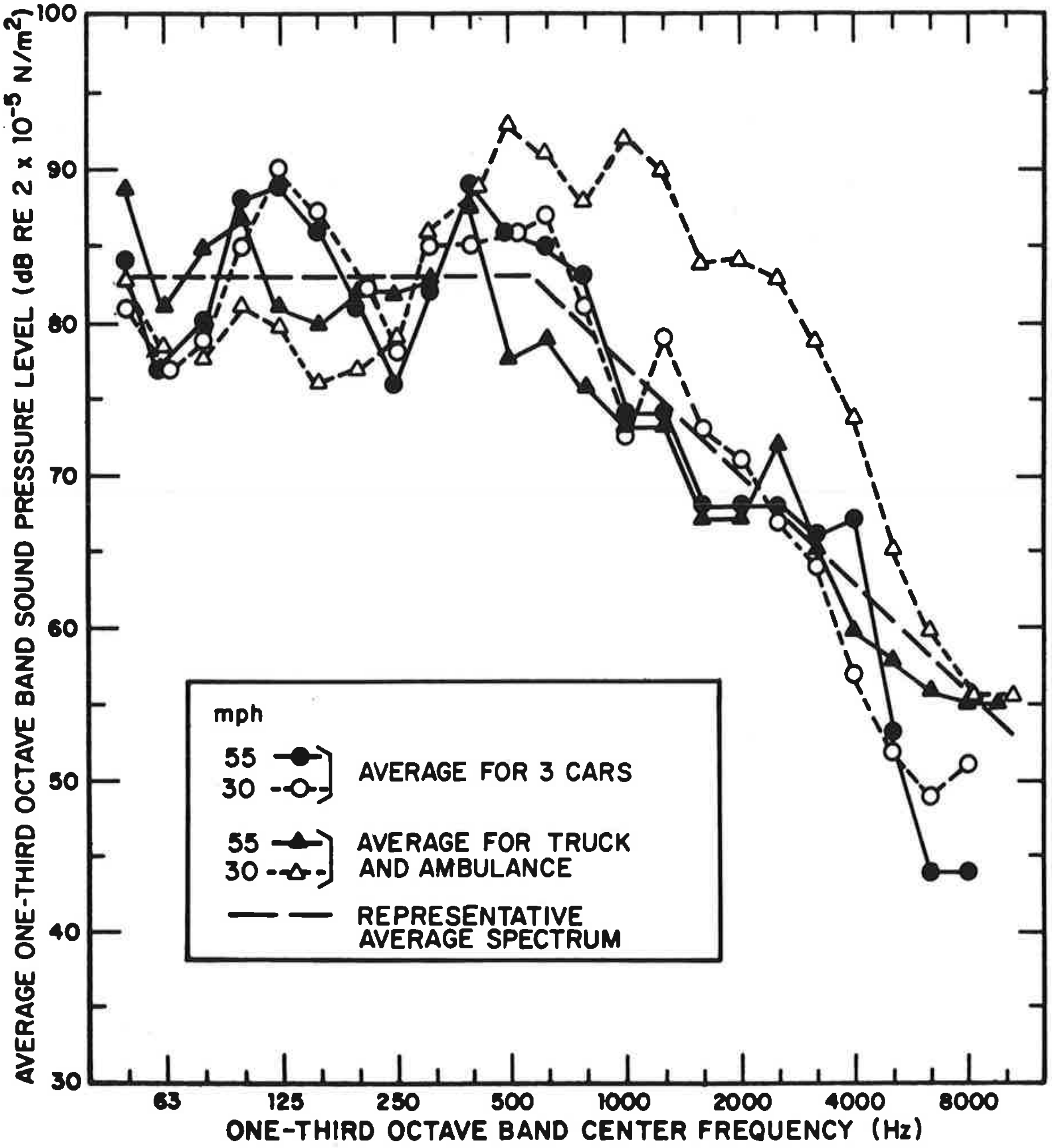

FIG. 25. DERIVATION OF A REPRESENTATIVE AVERAGE SPECTRUM FOR INTERIOR NOISE WITH RADIO ON.

Finally, Fig. 26 is a summary of all the representative average cases. The radio-on case applies to either suburban or rural areas. The urban spectrum is based on the maximum levels measured. It has the highest interior noise levels at the lower and higher frequencies, but generally does not set the worst-case masking level at the mid-frequencies associated with the siren sounds.

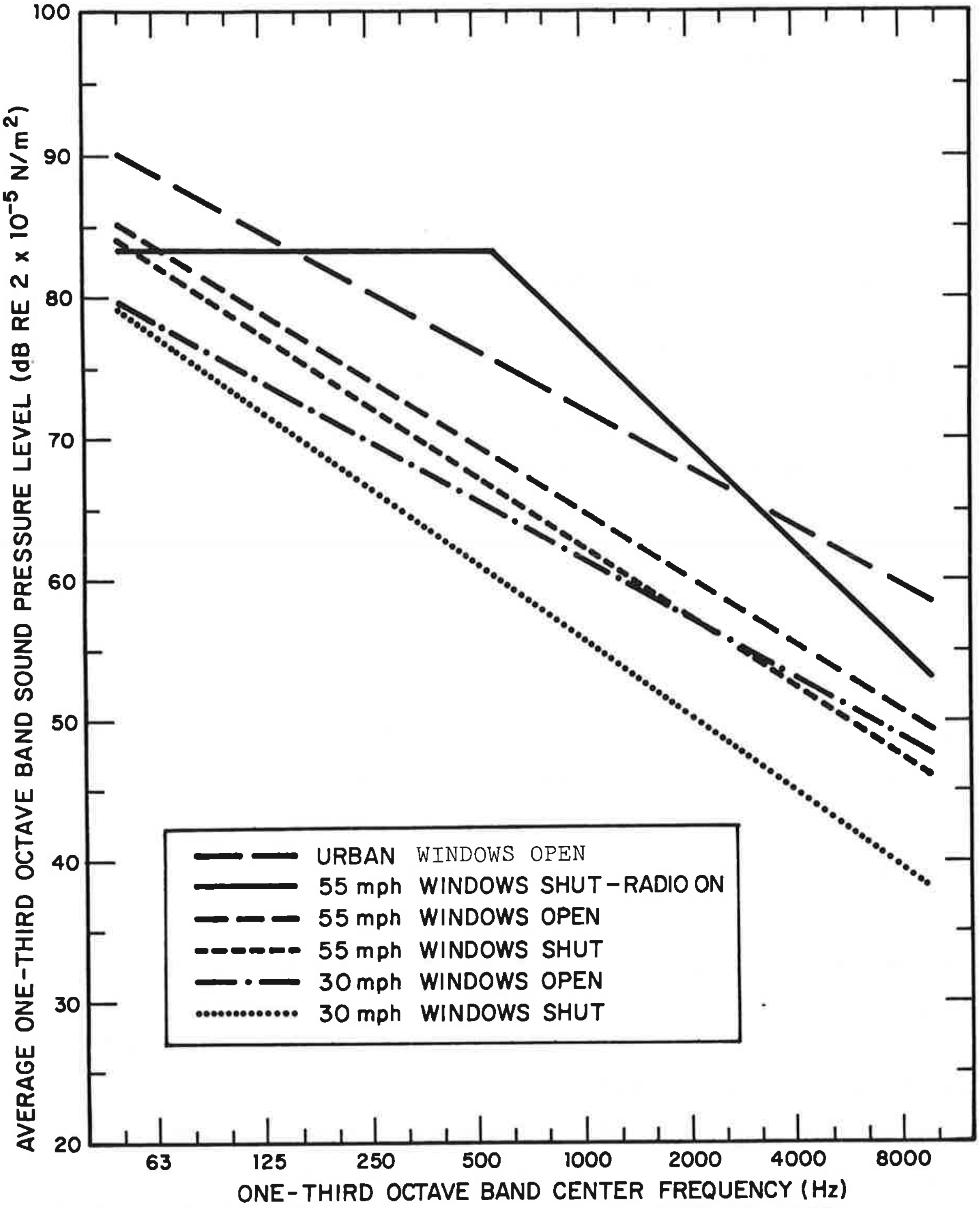

FIG. 26. REPRESENTATIVE AVERAGE SPECTRA OF INTERIOR NOISE.

5. VALIDATION EXPERIMENT

5.1 INTRODUCTION

An empirical test of warning signal audibility was undertaken under quasi-realistic conditions. All data were collected while test subjects were engaged in a simulated driving situation in an instrumented passenger car. Simulated tasks included turning the steering wheel toward alternately illuminated fender lights, maintaining a constant speedometer reading, and braking upon hearing warning signals.

5.2 METHOD

5.2.1 Test Signals

Selection. Six different warning signals were tested in this experiment, as shown in Table 9. Signals 1 through 4, produced by commercially manufactured devices, were recorded in a semianechoic room as discussed in Sec. 2 of this report. The recordings were filtered and level-shifted (for reasons discussed below), and made into loops for computer-controlled access from a cartridge tape machine.

Signals 1 through 3 were selected to be most representative of the set of warning signals initially recorded. This selection was based on a least-square fit to the mean of the 1/3-octave band equivalent levels (energy means) of all the devices. Thus,

TABLE 9. TEST SIGNALS USED IN VALIDATION EXPERIMENT.

Signal	Description
1	Carson SA 410 with 890R transducer, in "wail" mode, at 0° (on axis)
2	Dunbar-Nunn Unitrol 800 with Atlas HPR 370 transducer, in "yelp" mode at 0° (on axis)
3	Federal PA200 with CP100 high power transducer, in "hi-lo" mode, at 0° (on axis)
4	B and M S8 electromechanical siren at 12V operation, five seconds on, five seconds off, at 0° (on axis)
5	Frequency-modulated (3 Hz) sinusoid within 1/3-octave band centered at 1600 Hz
6	Signal 5 switched smoothly on and off at intervals of 333 msec.

The configuration of the test instrumentation is illustrated schematically in Fig. 27.

5.2.2 Test Subjects

Twenty-four licensed drivers (13 male, 11 female), ranging in age from 16 to 67 years (mean = 29.2; standard deviation = 16.9) served as test subjects. All were screened audiometrically to within 15 dB of ISO R-229. All were administered a cursory visual acuity check (Landolt rings) to determine that they could resolve one minute of arc. Drivers who normally wore corrective lenses wore their glasses during the test.

On arrival, subjects read an introductory paragraph of instructions, and subsequently heard tape-recorded detailed instructions while seated in the test car. The two sets of instructions were:

> <u>Introductory</u> (<u>printed</u>) <u>Instruction</u> - You are about to take part in an experiment concerned with automotive safety. A computer will monitor your performance while you "drive" a parked car. Your simulated driving tasks will include 1) maintaining a constant speed by referring to a speedometer, 2) steering toward certain lights, and 3) braking when you hear warning signals. Before you begin, the experimenter will give you brief hearing and vision tests. Once in the test car, you will receive detailed instructions. You will also have a practice session in the car before the computer starts to score your performance.
>
> <u>Detailed</u> (<u>oral</u>) <u>Instructions</u> - Throughout this experiment you will be expected to drive at a constant 50 miles per hour. The meter immediately in front of you on

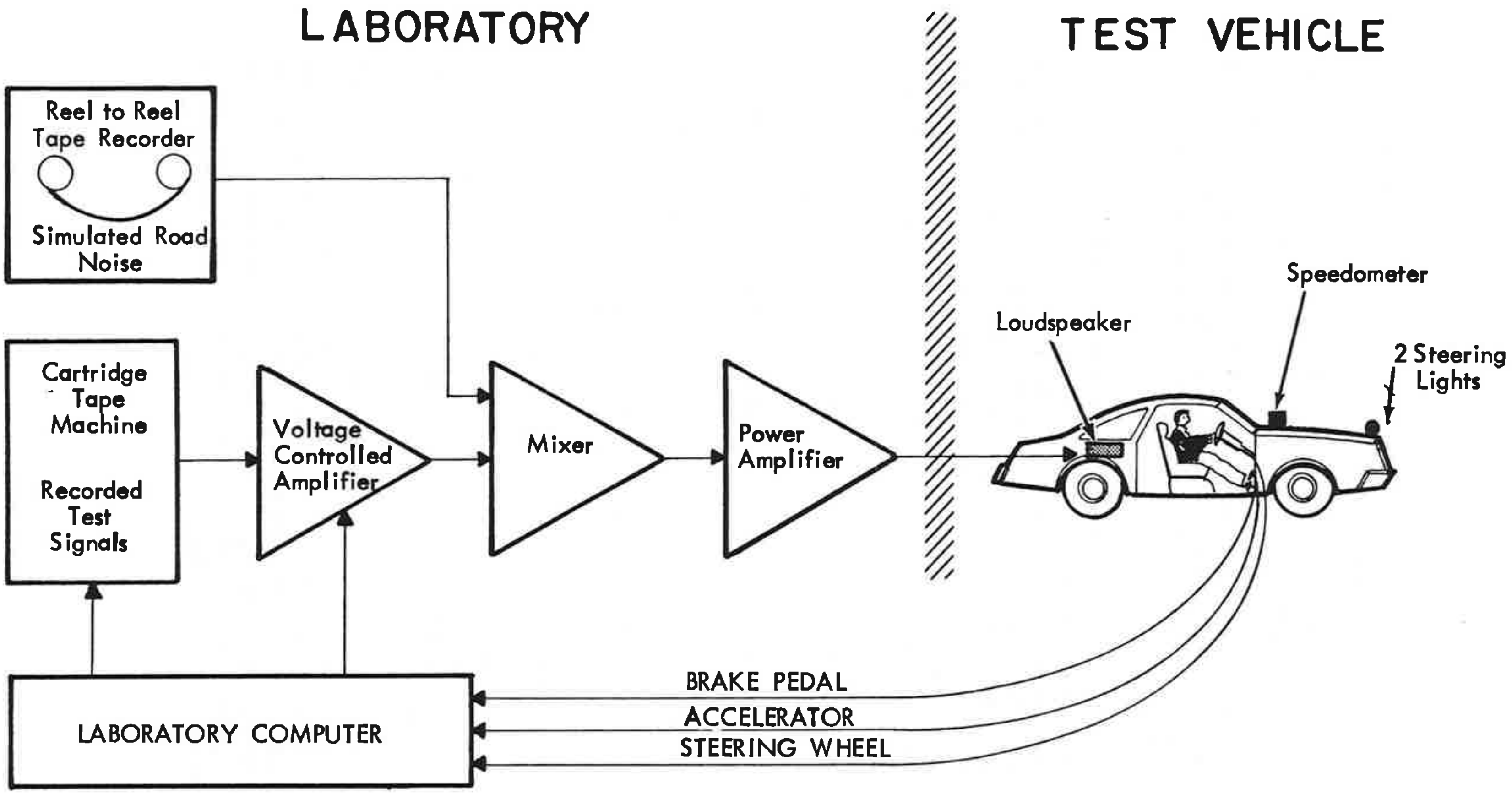

FIG. 27. INSTRUMENTATION FOR VALIDATION EXPERIMENT.

the hood of the car will be your speedometer. Step on the gas pedal now, and notice how the indicated speed varies.

There is a large red light on each front fender. One or the other of the lights will be illuminated at all times during the experiment. Every few seconds, the lights will change. Your job will be to turn the steering wheel toward the light that is on. The small yellow light on top of the big steering light will come on when you have turned the steering wheel far enough.

Finally, we would like you to take your right foot off the gas pedal and step on the brake pedal as quickly as you can when you think you hear something that sounds like a warning signal. The brake pedal is a bit stiff, so step on it hard with your right foot. The small light on top of the speedometer will come on when the brake pedal is pressed down far enough. Here's what the various warning signals you will be listening for will sound like: (all six signals played sequentially).

To encourage you to step on the brakes as quickly as you can, we will pay you ten cents above and beyond your hourly wages if you step on the brakes within one and a half seconds of the time that the warning signal starts. To make sure that you don't step on the brakes too often when there is no warning signal, we will deduct ten cents from your total bonus each time you step on the brakes when there really isn't a warning signal. If you don't step on the brake pedal after the warning signal has been on for several seconds, we will also fine you ten cents from your bonus.

To summarize your jobs, you should maintain a constant 50 miles per hour by stepping on the gas pedal, steer the car in the direction of the illuminated fender light by turning the steering wheel, and step on the brake pedal with your right foot as quickly as you can when you think you hear a warning signal.

The experimenter in the computer room will be able to hear anything you say. In a moment he will talk to you on the intercom to ask if you have any questions. During the testing we want to maintain a constant road noise environment. Thus, we would prefer that you concentrate on your driving tasks and not speak unless you have an important message, once the test starts.

The instructions were intended to stress that the experimenter was interested in all aspects of the simulated driving task, rather than in the aural detection task alone.

5.2.3 Experimental Design

As may be seen from the instructions, test subjects were required to carry out three tasks simultaneously. The two continuous tasks (steering and maintaining speed) may be thought of as foreground tasks. The background task (aural detection) was discrete, in the sense that a relatively small number of test signals was presented at random intervals.

The foreground tasks were intended merely to provide a plausible context within which the aural detection task could be performed. Scoring of these tasks was thus perfunctory. A time-on-target measure was computed for the steering task, consisting of the average time that the steering wheel was turned toward an illuminated fender light. The left and right lights were alternately illuminated in a normally distributed fashion, with a mean period of 7.0 sec and a standard deviation of 3 sec. This produced a moderately demanding, but nonfatiguing task. Graphic level recordings of the speed maintenance task were examined while the experiment was in progress to ensure that the subject was complying with the test instructions; however, no further use was made of this information.

The aural detection task was carried out in a noise environment shaped to approximate the representative average background noise used in evaluating warning effectiveness (see Sec. 7). The background noise spectrum in the test vehicle was produced by recording a shaped Gaussian noise signal that produced the desired levels in 1/3-octave bands at the driver's ear. The A-weighted level of the background was approximately 67 dB(A).

Each of the six test signals was presented twice, in random order, in each test session. The goal of the signal presentation schedule was complete temporal uncertainty from the driver's viewpoint. The range of intersignal intervals was 2 sec to 283 sec.

The time course of signal levels in each trial resembled the approach of an emergency vehicle. Each signal presentation commenced with the playing of the recorded warning signal at a predetermined level that was faintly audible but which was unlikely to cause a reaction. This level was computed for each signal such that its detectability index (d') was 4.0, a well-known threshold index in signal detection theory. If, after one sec, the test subject had not stepped on the brake pedal, the signal level was increased by 3 dB, a doubling of the signal-to-noise ratio (S/N) with consequent doubling of the value of d'. This process was repeated every second until: 1) the signal had been raised by 15 dB above its initial presentation level, or 2) a braking response intervened. Figure 28 is a

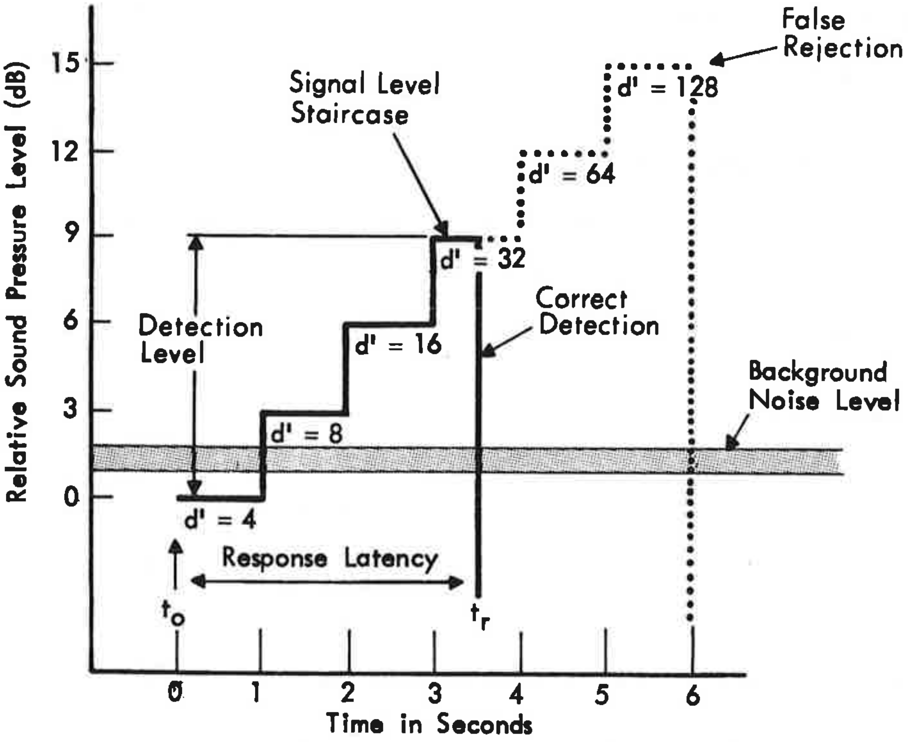

FIG. 28. TIME COURSE OF TYPICAL TRIAL. INITIAL SIGNAL PRESENTATION LEVEL WAS INCREASED 3dB EVERY SECOND FROM START OF SIGNAL (t_o) TO TIME OF BRAKE PEDAL DEPRESSION (t_r).

graphic representation of the warning signal levels in a single trial.

A response recorded within six sec of the starting time of a trail was considered a correct detection. The latency of such responses, measured from the starting time of a trial, was recorded along with the signal level at the time of the response. A brake pedal depression occurring when a signal was not presented was considered a false detection.

Data were collected in sessions of approximately 20-min mean duration. Subjects left the test vehicles for a short break between sessions, and completed four such sessions within two hours. A total of 48 signals was presented to each subject.

5.2.4 Test Vehicle

All testing was conducted in a two-door, 1976 Chevrolet Nova Concours. The vehicle was parked in a high bay laboratory area and mounted on jacks to lift its tires a few inches off the ground. The vehicle was instrumented in the following manner so that a laboratory computer could administer test conditions:

a. Two large (3.5-in. (11-cm) diameter) red lights were mounted at the corners of the front fenders. On top of each large red light was a small (1.3-in. (1-cm) diameter) yellow light. The appropriate yellow light was illuminated when the steering wheel was turned about 35 degrees left or right of center.

b. A "speedometer," consisting of a voltmeter with a single, highly visible 0-100-mph scale, was placed on the hood in front of the windshield such that it did not obstruct the driver's view of the fender lights. Depressing the accelerator pedal actuated the meter. On top of the "speedometer" was a small (1/2-in. (1-cm) diameter) red light that was illuminated when the brake pedal was depressed significantly to turn on the vehicle's brake lights.

c. A high-fidelity loudspeaker was placed in the back seat of the vehicle approximately 3 ft (1m) behind the driver's head. The loudspeaker was the source of both the simulated road noise and the warning signals.

d. An intercom was installed in the front seat to permit communication between the test subject and the experimenter.

Figure 29 is a photograph of the test vehicle.

5.3 RESULTS

5.3.1 Processing Of Data

The two major dependent variables, detection level and response latency, were related by the ascending method of limits trial procedure, which doubled the signal presentation level every second (see Fig. 28). Treatment of the raw data for these two variables was thus linked, as discussed below.

In any free response situation (one in which the subject is not constrained to respond during a fixed interval), a decision must be made about the temporal interval following a signal presentation during which a response is considered to be associated with the preceding signal presentation. In the present case, a "grace period" of 275 msec was allowed, during which a brake pedal depression was credited to the previous signal presentation level. This time period was selected because

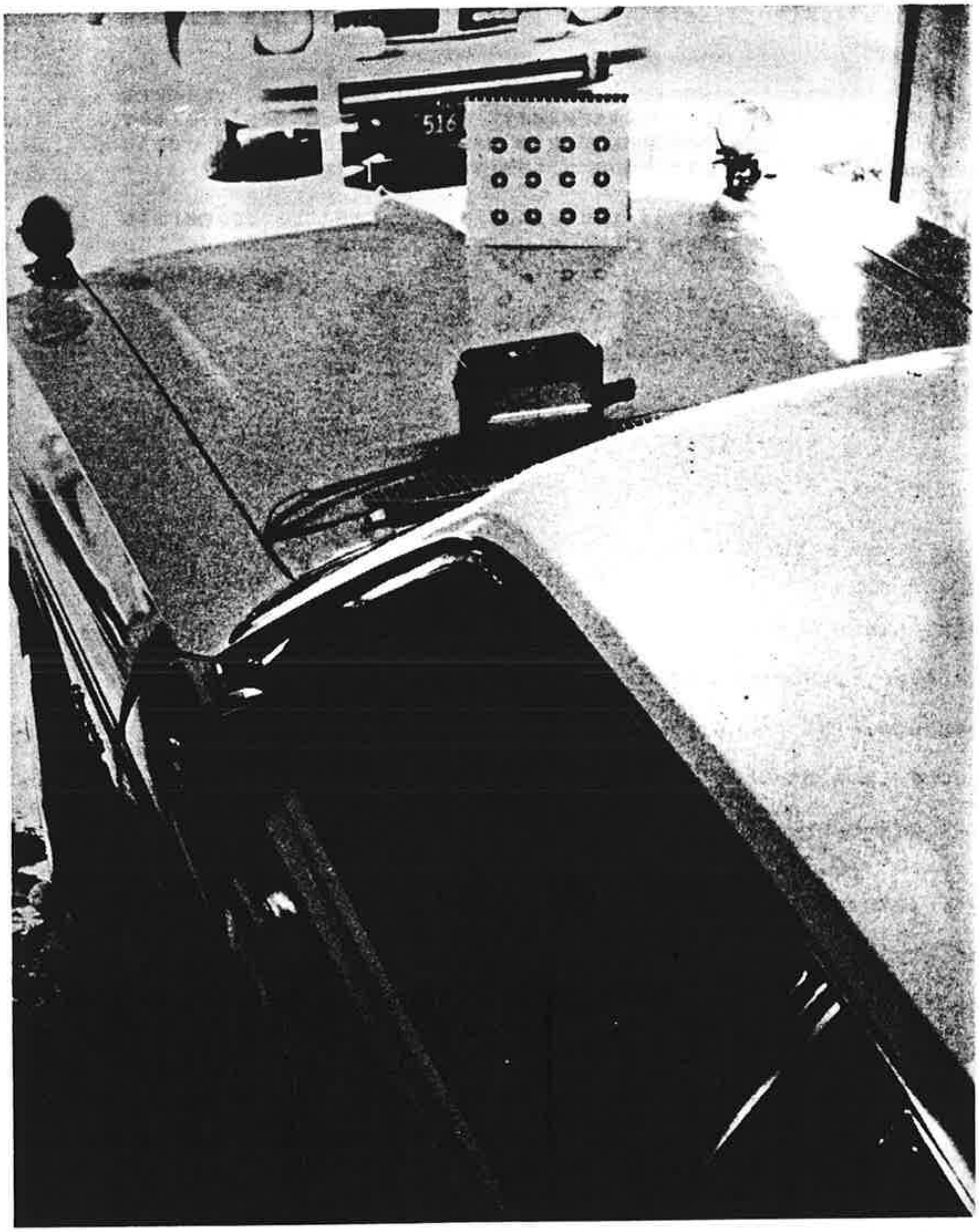

FIG. 29. AUTO CONFIGURATION FOR VALIDATION EXPERIMENT. (Test chart for visual acuity, shown on hood of vehicle, was not present during experimentation.)

it was felt to be somewhat shorter than the time required to remove the right foot from the accelerator and step on the brake pedal, after a decision to respond had been made.

The correction implied by this grace period was thus to halve the apparent detection level of any signal to which a response was made in less than 275 msec. This correction occurred for roughly a third of all responses.

As a further measure, data for the response made to the first presentation of each of the six signals were considered practice trials and were ignored for purposes of analysis.

5.3.2 Detection Level Findings

Table 10 contains average detection levels for all subjects expressed in d' units for each test signal. The first column contains this information for all 24 test subjects. The remaining four columns contain the same information for subjects grouped by sex and age.

The consistency with which the signals were detected by all subjects regardless of age or sex is noteworthy. Differences between the various groups for the same signals are typically on the order of 1 dB. The rank order of detectability of the six signals, with one minor reversal for the four older subjects, is constant. The range of detectabilities for the six signals is very close to 6 dB (ratios in d' values of 4:1 or less) for all

TABLE 10. DETECTION LEVELS (d' VALUES).

	All Subjects	N=11 Women	N=13 Men	N=20 Under 29	N=4 Over 64
Signal 1	43.1	37.9	47.5	37.0	73.5
2	17.4	18.0	16.9	16.0	24.4
3	25.3	24.4	26.1	25.1	26.3
4	18.0	18.9	17.2	17.6	20.0
5	50.2	46.0	53.7	46.5	68.6
6	67.9	67.8	68.0	64.7	83.7

groups of subjects as well.

No particular significance should be given to the actual detection levels of the various test signals, since these levels merely reflect the gain settings of the reproduction system chosen for each signal. Recall that the original signal recordings were both filtered and shifted in level to approximate vehicle interior spectra. Thus, it should not be inferred from these data that a particular audible warning device produces a more detectable signal than another. Inferences of this sort should be based instead on the warning effectiveness distances tabulated in Sec. 7.

Of much greater interest are the absolute values of the average detection levels. The test subjects required signal levels about 6 to 12 dB above those that an otherwise unoccupied observer would require, under laboratory conditions, to detect essentially all warning signals with a negligible false detection rate.

False detections were quite few. The average number of false detections per session for all observers declined from 1.96 to 1.09 from the first to fourth session.

5.3.3 Time On Target

All subjects performed the steering task without difficulty. The average time-on-target measure for all subjects increased from 81.7% to 86.6% over the four experimental sessions. There were no noteworthy differences in performance among subjects in this task; indeed, the standard deviation of the time on target measure for all subjects in the 1st session was only 2.4%.

5.4 DISCUSSION

5.4.1 On the Predictability Of Signal Detectability In Vehicles

The six warning signals were presented at levels that were equated on the basis of physical measurements of signal and noise levels in the test car. Thus, had the detectability of all the signals been perfectly predicted and had all of the signals been of equal arousal value, there should have been no differences in detection levels or response times to the six signals. In fact, the mean detection levels of the six signals for all 24 subjects varied by a factor of less than four, from d' values of 17.4 to 67.9.

The two artificial signals, numbers 5 and 6, which differed only by duty cycle, were predicted to be of equal detectability. The observed mean detection levels for the two signals corresponded to d' values of 50.2 and 67.8, which differ by only about 1 dB.

Overall, these results may be considered encouraging. They demonstrate that detectability predictions in vehicles can be made within ±3 dB for a variety of warning signals in actual use and that data from modest numbers of subjects can agree quite closely for similar signals.

5.4.2 On The Observed Detection Levels

The mean level for all subjects and test signals at which the detection response was made corresponded to a d' value of 37. In more controlled listening conditions, more experienced test subjects with greater amounts of practice would almost certainly have been more sensitive to the warning signals than were the current test subjects.

The important point, however, is that the test subjects were quite consistent in their signal-to-noise ratio requirements for the braking response. Signals characterized by a d' value of 37 are not merely highly detectable -- they are distinctly recognizable and clearly audible.

In other words, an "effective" warning signal for the test subjects (one upon which a decision to step on the brake pedal could be based) required a signal-to-noise ratio 9 dB greater than that needed merely to detect a signal reliably.

This relationship between a mathematically defined index of signal detectability and the "effectiveness" of a warning signal makes possible the first quantitative estimates of warning signal level requirements. Such estimates are embodied in the dimensions of the warning effectiveness distances presented in Sec. 7.

5.4.3 On The Response Latency Data

Since the six test signals varied by a factor of four in detectability, but only by tenths of seconds in response latencies, it appears (to a first approximation, at least) that signals of equal detectability give rise to equal response times. Given that response latency is accepted as an adequate measure of the "arousal value" or "attentional demand" of a warning signal, this conclusion lends support to the hypothesis that warning signals of equal detectability are equally effective.

The practical significance of this conclusion is that it greatly simplifies selection of warning devices. It suggests, for example, that there is no reason to expect manipulations of the parameters of warning signals (apart from signal levels) to produce an especially arousing or effective device. It also permits greater confidence in the use of warning effectiveness distances, since they can be expected to be generally applicable to all sorts of warning devices.

6. LOCALIZATION EXPERIMENT

6.1 SIGNIFICANCE OF DIRECTIVITY DETERMINATION

The driver of an automobile might first become aware of the presence of an emergency vehicle by hearing its audible warning device. It is then useful for him to know the direction from which the sound is approaching in order to take the most appropriate evasive action. The process by which a listener identifies the direction from which a sound arises is called localization.

The localization of an acoustic source is aided by the difference in phase of the signals at the observer's two ears (the interaural time delay) [22]; and by their difference in amplitude [23] due to refraction around the head and shoulders. It is also possible that refraction by the ear lobes aid in localization [24]. Finally, by moving his head a listener can improve localization by altering the angle of incidence of the sound waves. The apparent direction from which a signal is received within a motor vehicle can be significantly affected by transmission of the sound through the structure of the vehicle or through open windows. In addition, the reflection of the sound from buildings, the road, and other vehicles can alter the apparent sound source direction outside a vehicle. As a result, the determination of the direction of an emergency vehicle by a driver is usually accomplished by sight -- following his acoustic perception. For example, one study of the detection of trains at road/rail grade crossings concluded that the sound of the train whistle alerts the automobile driver, but the location of the train is accomplished by sight [25].

Accordingly, an experiment was conducted to determine whether or not localization of emergency vehicle audible warning devices by drivers is a significant factor.

6.2 LOCALIZATION EXPERIMENT

Each of five blindfolded subjects was tested initially in an open air situation without any vehicle present. This experiment served as a control to assure that the ability of the subjects to determine direction of a sound source was not impaired and to establish a baseline for this ability. Subjects seated in a chair heard a siren located at 20 randomly selected positions on a 60-ft (18-m) radius circle around the chair. They were requested to identify the apparent direction of the source by pointing according to the instructions given in Table 11. The experimenter identified each response within one of eight 45-degree sectors, according to the layout sketched in Fig. 30.

The test was then repeated with the subject located at the same position, but in the driver's seat of an automobile with all windows closed. Finally, another set of tests was conducted with the front passenger window fully open. The details of these

TABLE 11. SAE - SIREN LOCATION EXPERIMENT: INSTRUCTIONS TO SUBJECTS.

1. You will be seated, with the tester, either in the open or within an automobile.

2. You will be blindfolded.

3. At intervals, a siren of the type used on fire engines, will be operated.

4. At each sound of the siren - when you first determine that you hear the siren, you are to point, with extended arm and finger, immediately at the direction from which you consider the sound is coming. You must point *immediately* with either arm and you may move or turn your body to point.

5. Please, then hold that direction until the tester indicates you may relax. If you later feel that you were mistaken, and that, as the sound becomes louder or lasts longer, it is coming from a different direction to your first impression, then please tell the tester. He may or may not then ask you to indicate your second impression of the direction of the siren.

6. You may turn your head or move in the seat, if you so desire, but the *objective* of this test is to determine *your immediate opinion* of the location of the siren when *you first hear it.*

7. Listen for the instructions of the tester.

8. If you have any questions concerning the test - then ask the tester.

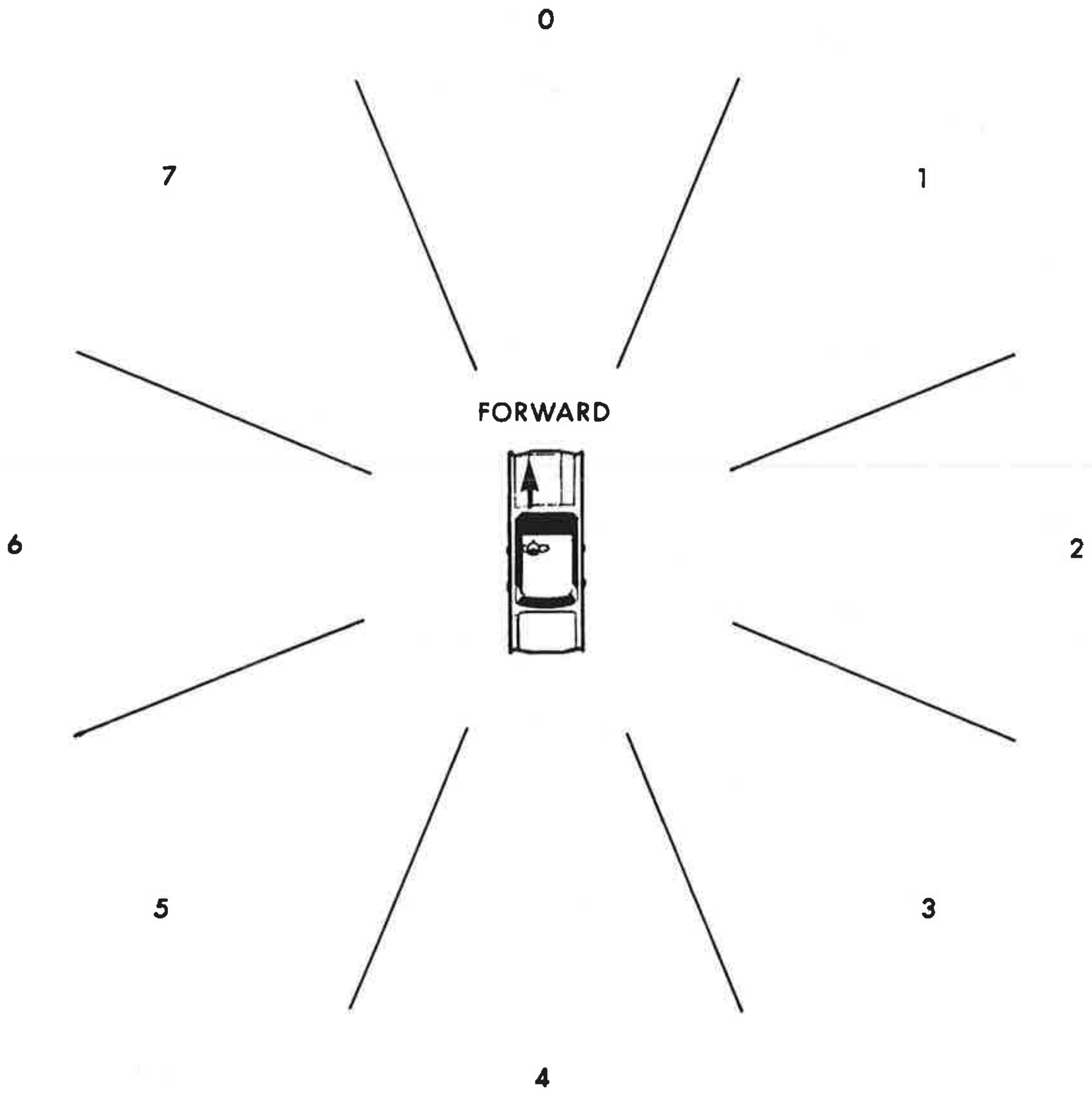

FIG. 30. SECTOR NOTATION FOR LOCALIZATION EXPERIMENT.

experiments are summarized in Table 12.

To avoid the subject's identifying the siren positions from the noise caused by moving it, a radio was turned on loud enough to mask any such noise between siren sounds. Particular emphasis was placed on the siren positions exactly forward and behind the vehicle, since it was suspected that the symmetry of the situation regarding phase differences at the subject's ear might lead to confusion between identifying these two directions.

Each individual judgment of direction was termed _correct_, if the subject pointed into the 45-degree sector containing the siren, and _incorrect_ when he pointed outside of this sector.

6.3 RESULTS

The results of the tests for five subjects are given in Table 13 in the form of correct and incorrect judgments. The individual and mean percentage correct results and the standard deviation of the results are shown in Fig. 31, and the individual results for the three tests are shown in Figs. 32, 33 and 34. In overall terms, the subjects could almost always tell the direction of the source in the open air situation. But once inside the car, they were generally unable to locate the source. This result was somewhat improved for the case when the passenger's window was open. However, with the windows closed,

TABLE 12. DETAILS OF THE DIRECTIVITY DETECTION EXPERIMENT

Signal	Source: B & M Siren Manufacturing Co., Model 58M9 Electro-Mechanical Siren, Serial No. 38655 Frequency: Sweep from 380 Hz to 800 Hz fundamental, harmonics up to 2000 Hz. Duration: 3 sec. Time between signal presentations: 40 sec.
Distance and Direction	Siren Distance: 60 ft (18 m) radius circle Direction: Random
Terrain	Flat parking lot, asphalt surface, no nearby vertical surfaces
Weather Conditions	No wind, dry, partially sunny
Automobiles Used	1974 AMC Gremlin (3 subjects) 1970 Ford Maverick, 2 door (1 subject) 1970 VW squareback (1 subject)
Ambient Noise Conditions	Engine idle Fan "Off" or "Low" Windows closed (except for the test series where passenger side window is opened)

TABLE 13. RESULTS OF DIRECTIVITY EXPERIMENT

	In Open Area			In Automobile: Windows Closed			In Automobile: Front Passenger Window Open		
Subject	Correct	Total	%	Correct	Total	%	Correct	Total	%
1	14	19	73.7	4	20	20.0	11	21	52.4
2	18	20	90.0	6	20	30.0	8	20	40.0
3	20	20	100.0	3	20	15.0	8	20	40.0
4	19	20	95.0	7	20	35.0	9	20	45.0
5	19	20	95.0	6	20	30.0	2	20	10.0
Total	90	99	91.0	26	100	26.0	38	101	37.6

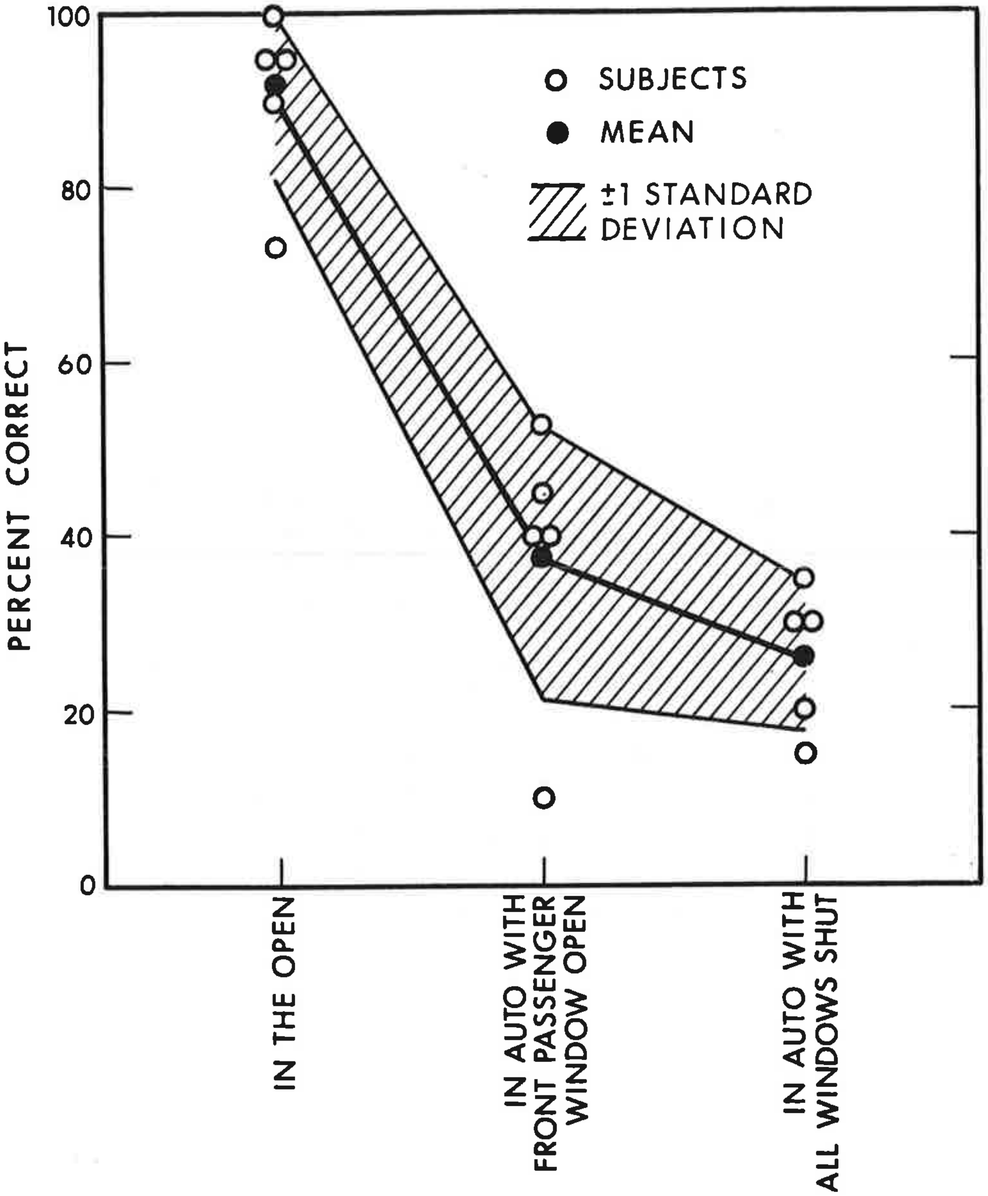

FIG. 31. RESULTS OF DIRECTIVITY EXPERIMENT.

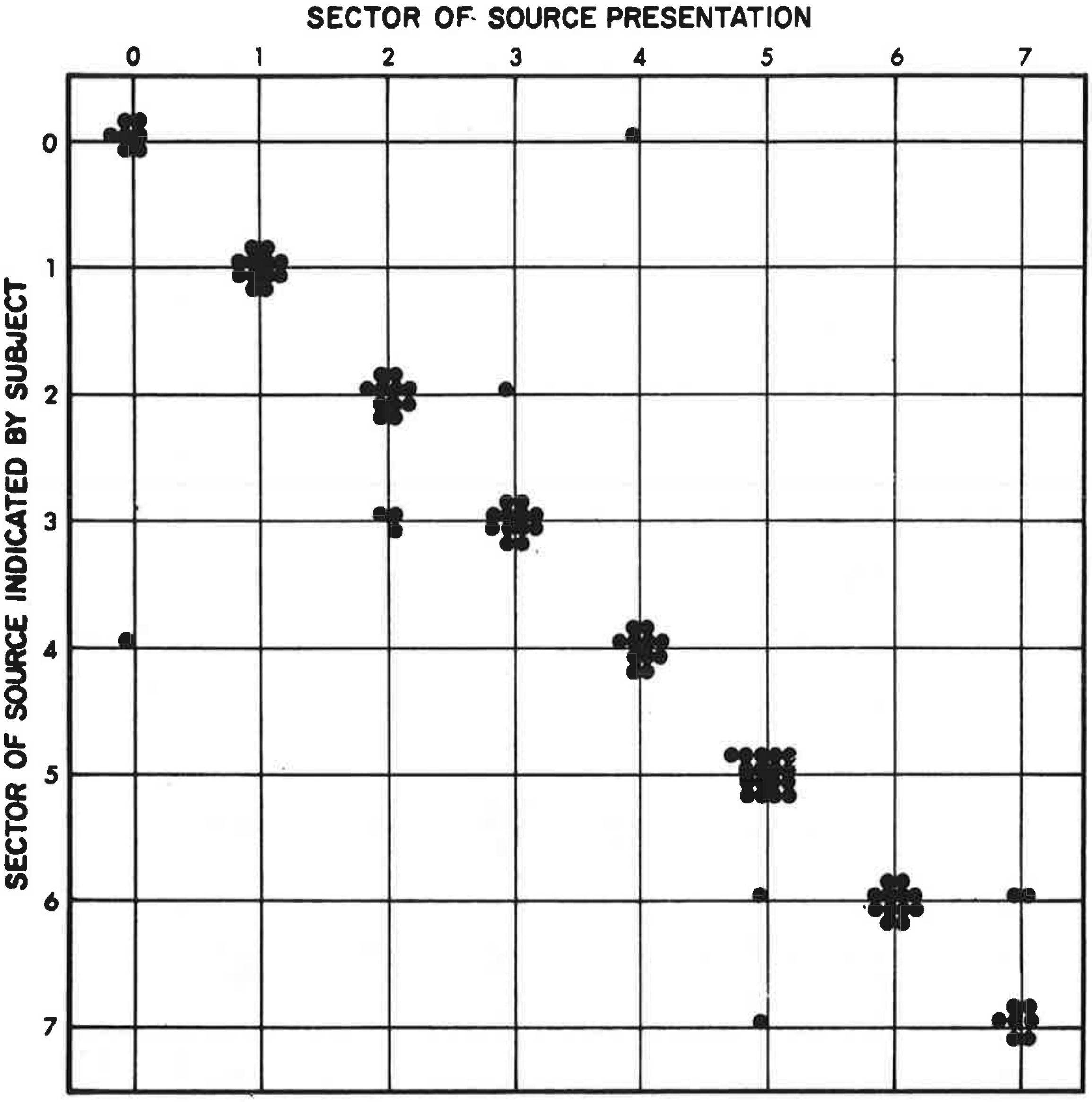

FIG. 32. TEST RESULTS FOR LOCALIZATION EXPERIMENT: SUBJECT IN AN OPEN AREA.

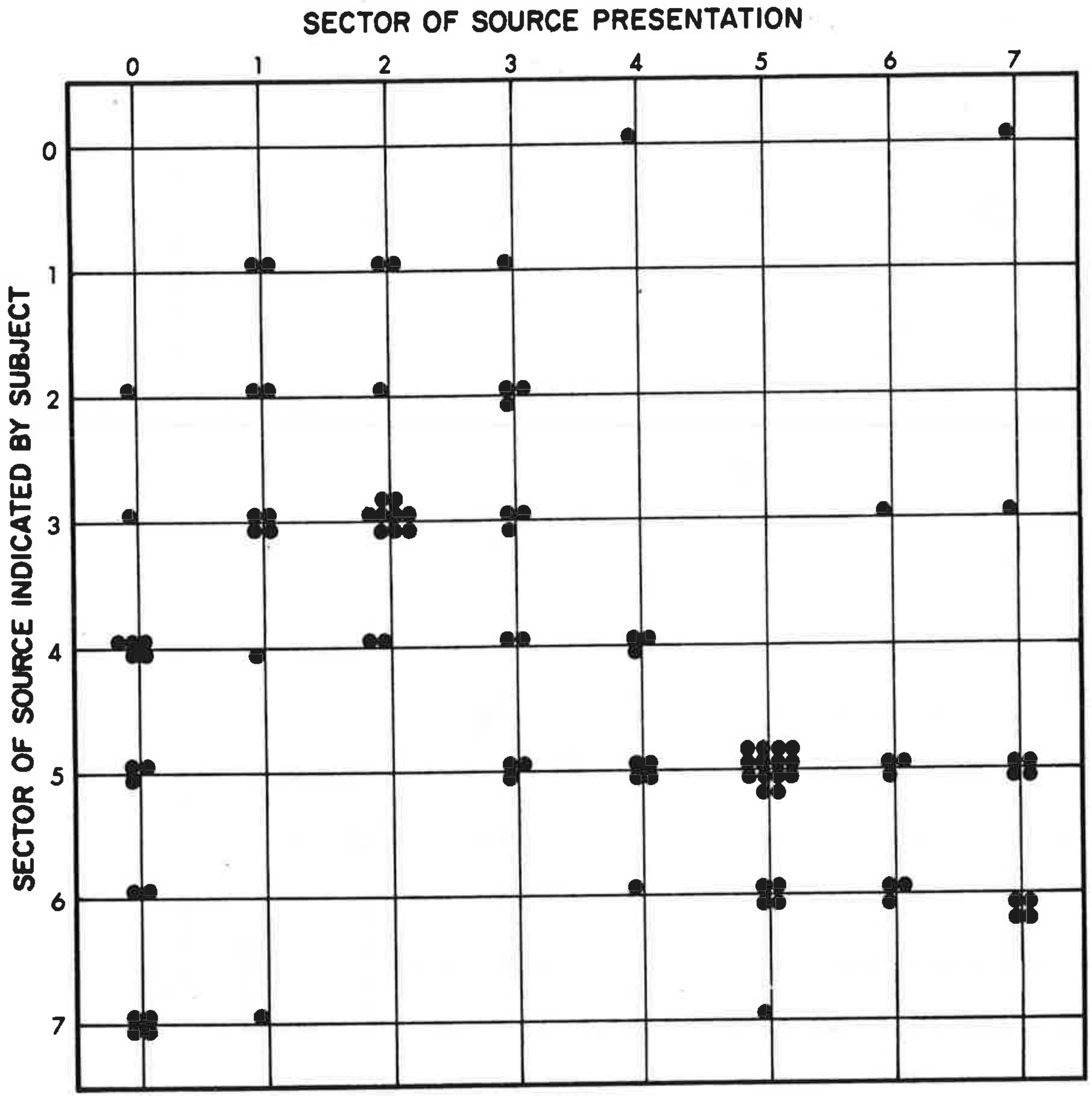

FIG. 33. TEST RESULTS FOR LOCALIZATION EXPERIMENT: SUBJECT IN AUTOMOBILE, WINDOWS CLOSED.

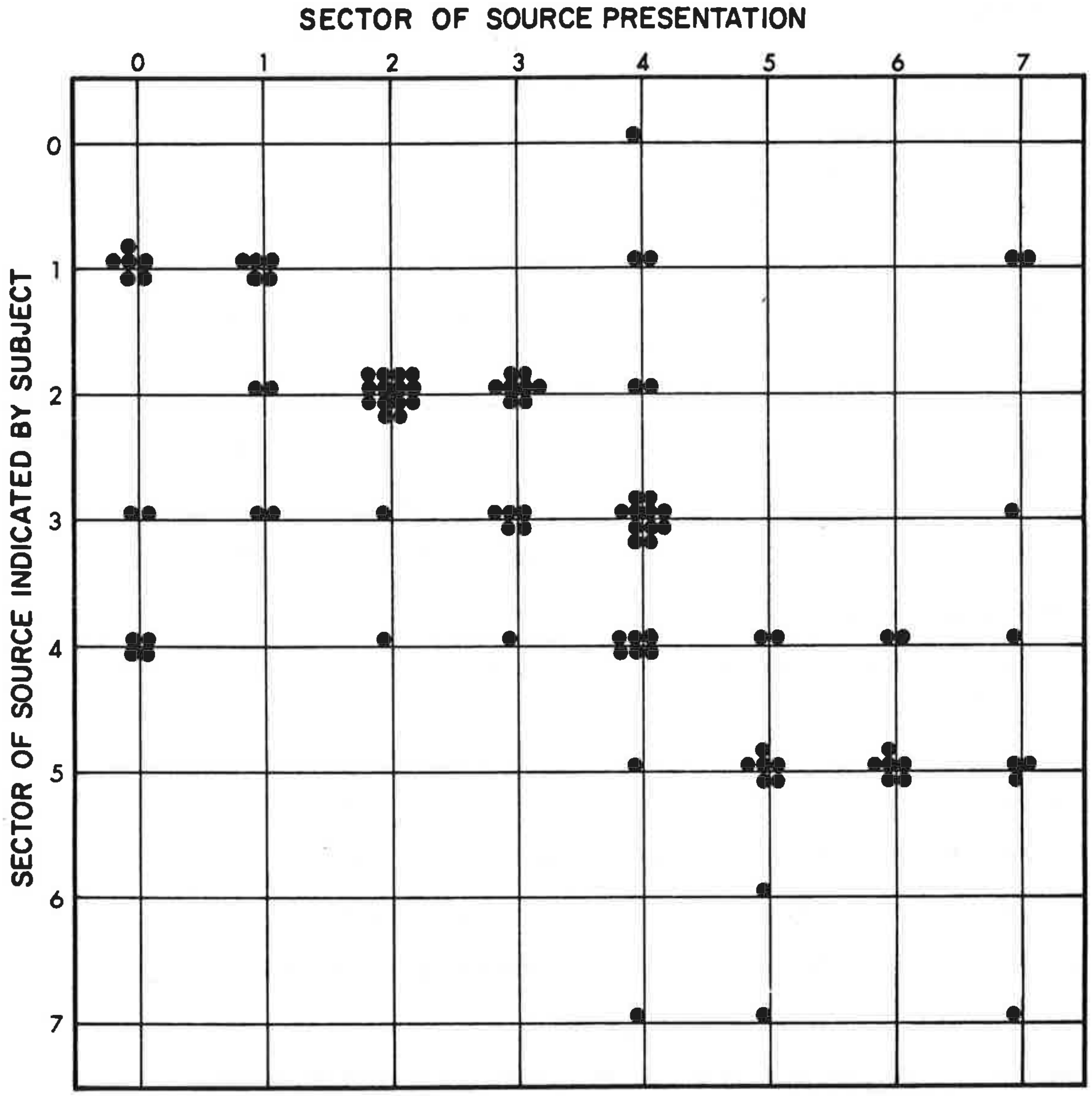

FIG. 34. TEST RESULTS FOR LOCALIZATION EXPERIMENT: SUBJECT IN AUTOMOBILE, FRONT-PASSENGER SIDE-WINDOW OPEN.

the subjects could only judge the source direction correctly in one-fourth of the presentations. By chance alone, they would be expected to get the correct answer one-eighth of the time.

The most marked trend in the data was for the closed vehicle case, in which there was a tendency to mistake the source location as normal to or just behind the driver on the side of the source. With the window open, there was generally no problem in locating the source when it was opposite the open window (Fig. 34).

These results suggest that when the source was to the side, the subject in the car generally indicated the correct side. When the source was immediately behind or forward of the vehicle, the subject incorrectly indicated the side of 65 of the occasions and, more critically, the opposite direction on 17 of the occasions.

In most cases, the subjects in the automobile indicated either the correct direction (31) or within ±45 degrees of the correct direction (38). At first glance, this may seem to be reasonably good localization; however, these results mean that about every fourth trial is completely at variance with the correct location. It should also be realized that these tests were conducted on a flat open terrain, with no reflecting surfaces or other nearby vehicles to distort the source field outside the vehicle. Greater difficulty in siren localization might be expected in a real traffic situation. As a result, it was concluded that siren source localization is a generally unreliable clue to emergency vehicle direction, and that further studies of driver localization were unjustified.

7. WARNING EFFECTIVENESS DISTANCES

7.1 DEFINITION

A definition of the warning properties of an emergency vehicle siren can be based on the concept of isodetectability. An isodetectability contour is the locus of all points at which a signal from an AWD is equally detectable. The isodetectability contour thus encloses a space within which a signal may be detected with specified correct and false detection rates.

Given any specified value of the detection coefficient d', the region of detectability can be constructed for any particular source-receiver combination. The prediction can be source-oriented or receiver-oriented. A receiver-oriented prediction can be used to indicate the distance from the driver of an automobile at which the background noise and propagation effects limit the signal-to-noise-ratio spectrum of an audible warning device to specified detection values. A source-oriented prediction may be used to represent the distance from a siren at which its signal, emitted in a given ambient noise background and attenuated by propagation, gives rise to the certain signal-to-noise ratios.

For present purposes, source-oriented predictions offer the greater utility since they: (1) permit direct comparisons among different audible warning signals, (2) allow consideration of nonisotropic propagation conditions, and (3) correspond more closely to intuitive notions of "warning distances".

To calculate source-oriented warning-effectiveness distances, the variables that influence the signal-to-noise ratio spectrum at the driver's ears must be specified. These variables include those that affect source level (e.g., mode of operation, orientation of the source, variability of source level with time) as well as those that affect the propagation path (hemispherical dispersion, ground impedance, atmospheric absorption, vertical wind and temperature gradients, barriers, vehicle insertion loss). Finally, the efficiency of the receiver with respect to an ideal detector must be known.

In prior sections of this report, representative average values for many of these variables have been adopted. Without such representative average values, meaningful comparisons among different audible warning devices would not be possible. The disadvantage of adopting such standard conditions, however, is that the results developed from them cannot be applied to any one specific case.

Some caution is needed in interpreting the results on the basis of representative average conditions. One cannot determine that a given warning signal will or will not be effective on a particular street. If such a determination were desired, the result would have to be based upon the specific conditions existing at the moment at which the determinations were to be made.

Perhaps the best use of warning effectiveness distances is for purposes of comparison. Under the same set of standard conditions, audible warning devices may be compared to determine whether one offers any significant advantage over the other. In addition, stopping distances can also be calculated to determine the absolute "effectiveness" of a warning signal.

7.2 PROPAGATION OF SOUND AND MODEL SITUATIONS

The propagation of sound through the atmosphere from a source near the surface to some remote receiver is a complex phenomenon. It is influenced by the detailed properties of the atmosphere and of the reflecting surfaces along all the sound wave paths from the source to the receiver. These properties change with time and location in such intricate ways that it is impractical to define them completely.

The properties of interest of the medium through which the sound is transmitted include:

-> The geometry of the propagation environment, to a level of detail (scale) smaller than the wave-length of the sound wave of interest

-> The impedances of all reflecting and scattering objects

-> Classical and molecular absorption in the atmosphere (which are a function of temperature and humidity)

-> Refraction in the atmosphere due to gradients in the local speed of sound.

As the situation changes from urban to open countryside, the relative significance of these various factors can alter. In downtown areas, the streets are surrounded by tall buildings, and propagation is analogous to that in a complex-shaped semireverberant room: the acoustic properties of the boundaries are more important than those of the air. At the other extreme, in open countryside, the temperature and wind stratification of the atmosphere are very important, and the properties of boundaries can be of lesser importance.

For the purpose of this analysis, three sample models have been utilized: one each for urban, suburban, and rural propagation conditions. Sufficient experimental data to describe these propagation conditions have been found in the literature, so that further experimentation during this program has been unnecessary.

Urban Model

An urban area is one in which 75 percent or more of each side of the roadway is lined with structures. The average distance of the structures from the roadway is 50 ft (15m) or less. They are generally more than three stories high and the ground along the sides of the road is predominantly paved.

With the growing international interest in traffic noise, numerous studies have been made of sound propagation along urban streets [26-30]. On the basis of all of these studies, but most notably those of Refs. 28 and 29, the urban propagation model assumes 6 dB per doubling of distance, plus standardized atmospheric absorption [31] for line-of-sight propagation up and down the street traveled by the vehicle with the siren. An additional 10-dB loss (at all frequencies) is allowed for propagation around corners into side streets.

Suburban Model

A *suburban* area is one in which 25 to 75 percent of each side of the road is lined with structures. Generally, the structures will be three stories or less in height and 50 to 100 ft (15 to 30m) from the roadway. The ground along the sides of the road will generally be planted.

The suburban scenario represents a transition between the reflection-dominated urban propagation condition and the atmosphere-dominated rural one. This situation has been studied by several investigators [32,33,34]. It has been reported that suburban propagation is very similar to that in rural areas except for the shielding effects of buildings. Because the situation in which vehicles converge at an intersection is of particular interest in this study, the configuration shown in Fig. 35 is selected as a suburban model. The diagonal barrier

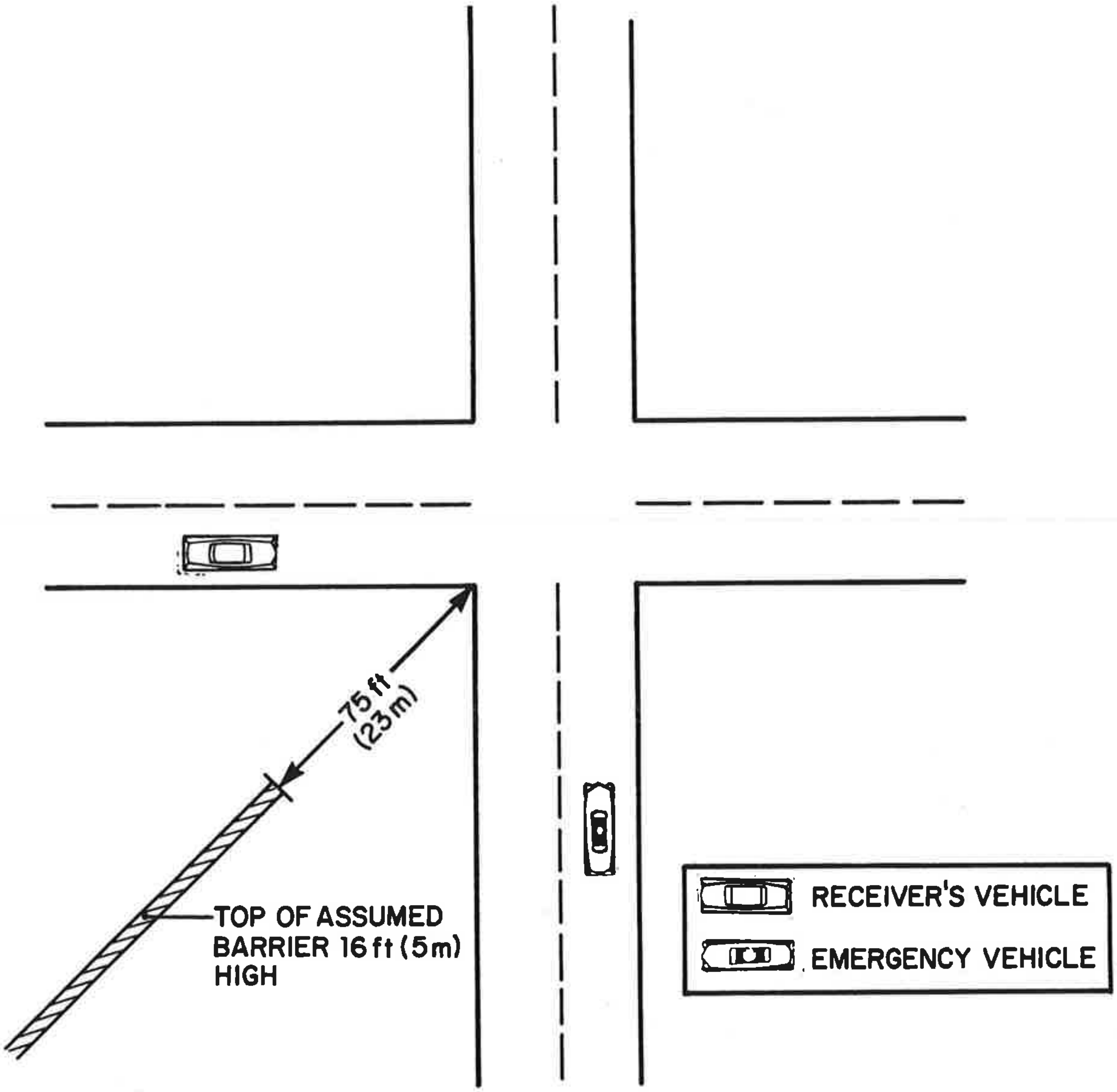

FIG. 35. SITUATIONS PROPAGATION FOR SUBURBAN MODEL.

[36] simulates the effect of suburban residences spaced along the sides of the roadway.

For configurations where the barrier is not effective, hemispherical divergence (6 dB/doubling of distance) and atmospheric absorption are assumed.

Rural Model

A *rural* area is defined as one in which 25 percent or less of each side of the road is lined with structures. Generally, the structures are 100 ft (30m) or more from the roadway, and three stories or less in height. The ground along the sides of the road is predominantly unpaved and planted.

In the rural model, atmospheric and ground surface effects predominate. Barrier shielding by buildings and the effects of reflections from buildings are assumed to be negligible. Diffraction due to vertical wind and temperature gradient has been assumed negligible over the range of distances of interest, so that the propagation model assumes only hemispherical divergence and atmospheric absorption.

7.3 ACOUSTIC DATA

7.3.1 Acoustic Signals For Audible Warning Devices

Representative characteristics for the four basic siren signals (wail, yelp, hi-lo, and mechanical) developed in Sec. 2 were used to generate effectiveness distances for different sirens in varying acoustic conditions. The actual 1/3-octave band sound level spectra used in the analysis are taken from Figs. 6-9. In examining crossroad situations, it was assumed that the two vehicles (the source and the receiver), are at equal distances from the corner. This approximates the most hazardous configurations and allows the 45-degree radiation levels of the sirens to be used for the suburban and rural situations.

7.3.2 Vehicle Acoustic Properties

Based on the results of Secs. 3 and 4, three vehicle insertion loss and background noise spectra were chosen for examination. For the urban situation, the maximum sound levels measured inside vehicles were combined with the mean values of insertion loss for the open window case. For the suburban situation, the 30-mph interior sound levels with the window open were combined with the appropriate mean insertion loss values. This combination yields a potentially maximal detection, because of the low levels of interior noise and the small values of insertion loss. For the rural situation, a vehicle traveling at 55 mph with the radio playing and the insertion loss of a closed window configuration was chosen.

7.3.3 Psychophysical Variables

The average signal levels at which reliable responses were made in the verification experiment (see Sec. 5.4) were used to infer suitable values for the probabilities of audible detection. As discussed in Sec. 5.4.2, these values require a d' value of 37. The driver's efficiency (η) with respect to an ideal energy detector was taken to be 0.4, the value determined by previous research in the signal detection field [2]. These variables were held constant for all three models. Referring to the d' equation shown in Sec. 1, these data are used to determine the relationship between signal-to-noise ratio required for detection in each 1/3-octave band.

7.4 CALCULATION OF WARNING EFFECTIVENESS DISTANCES

For each model situation, the 1/3-octave band sound level required for detectability outside the receiving vehicle was determined as follows: First, the representative average interior noise level (from Sec. 4) was added to the appropriate insertion loss (from Sec. 3). Then the necessary signal-to-noise ratio spectrum (as required for a d' of 37) was added to the sum. The result of this process is the sound level in any 1/3-octave band that must be produced just outside the receiving vehicle. These hypothetical spectra are illustrated in Figs. 36-38. They show the high levels of sound necessary to produce detection in

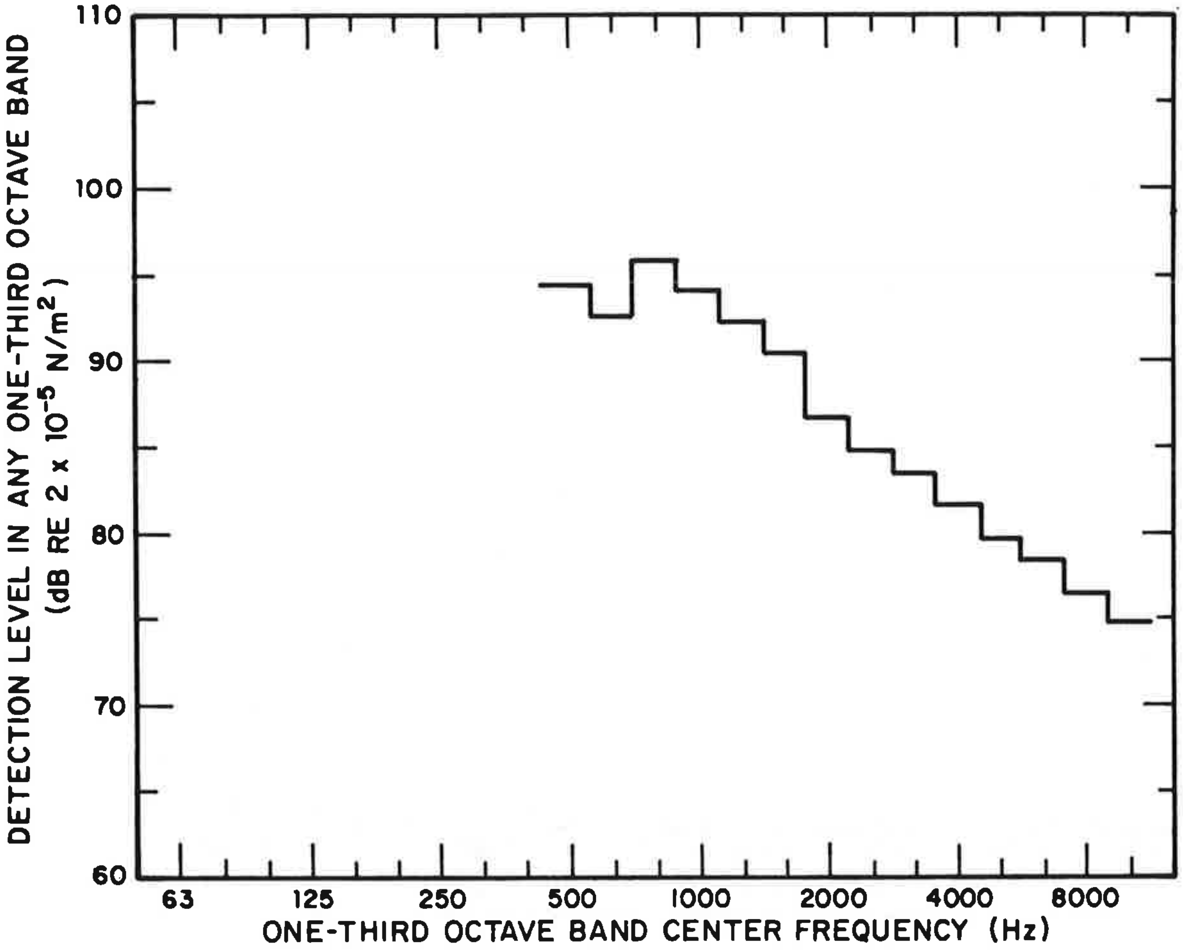

FIG. 36. SOUND PRESSURE LEVEL THAT MUST BE ACHIEVED, IN ANY 1/3-OCTAVE BAND, IMMEDIATELY OUTSIDE THE RECEIVING VEHICLE IN ORDER FOR DETECTION TO OCCUR: URBAN MODEL WITH WINDOWS OPEN

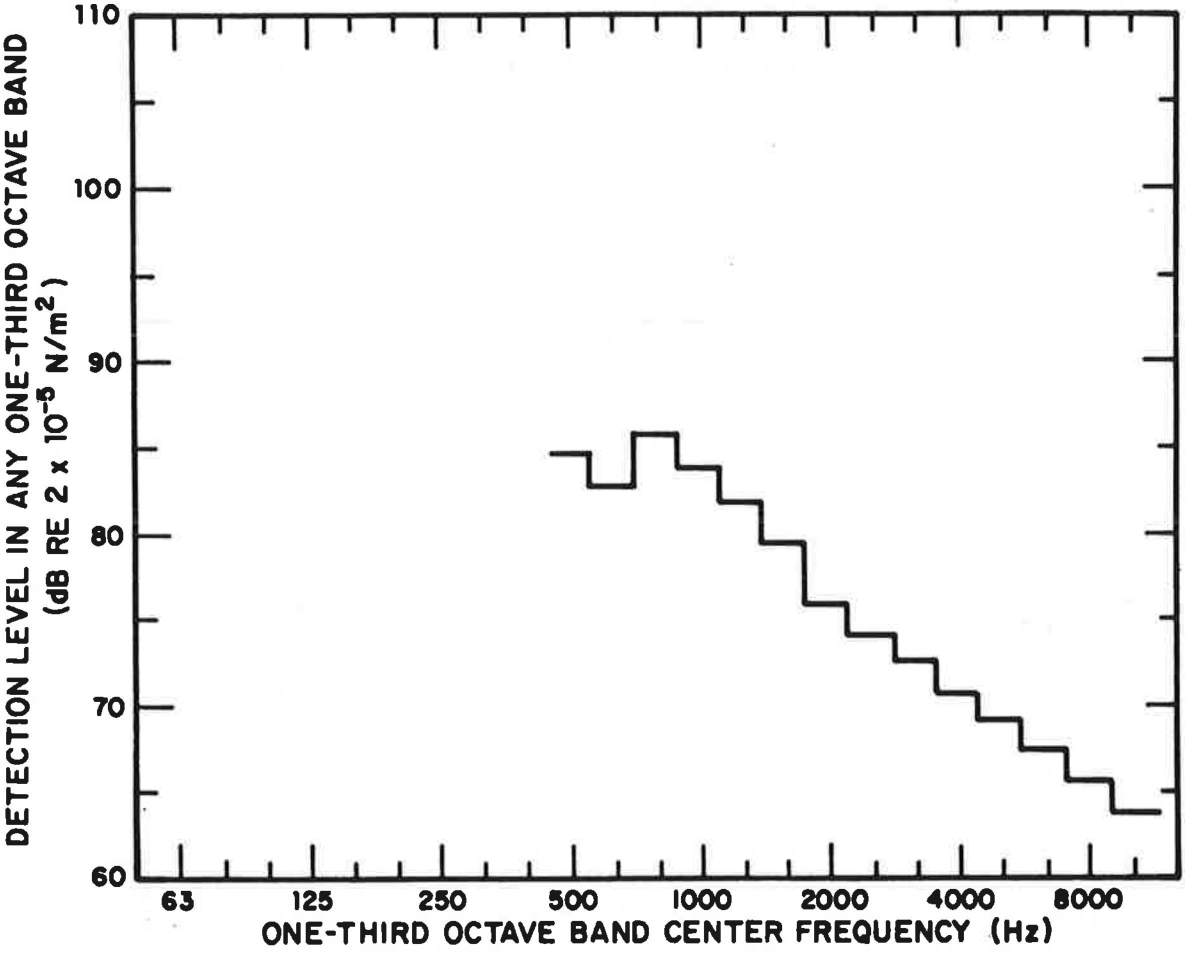

FIG. 37. SOUND PRESSURE LEVEL THAT MUST BE ACHIEVED, IN ANY 1/3-OCTAVE BAND, IMMEDIATELY OUTSIDE THE RECEIVING VEHICLE IN ORDER FOR DETECTION TO OCCUR: SUBURBAN MODEL, 30 MPH WITH WINDOWS OPEN

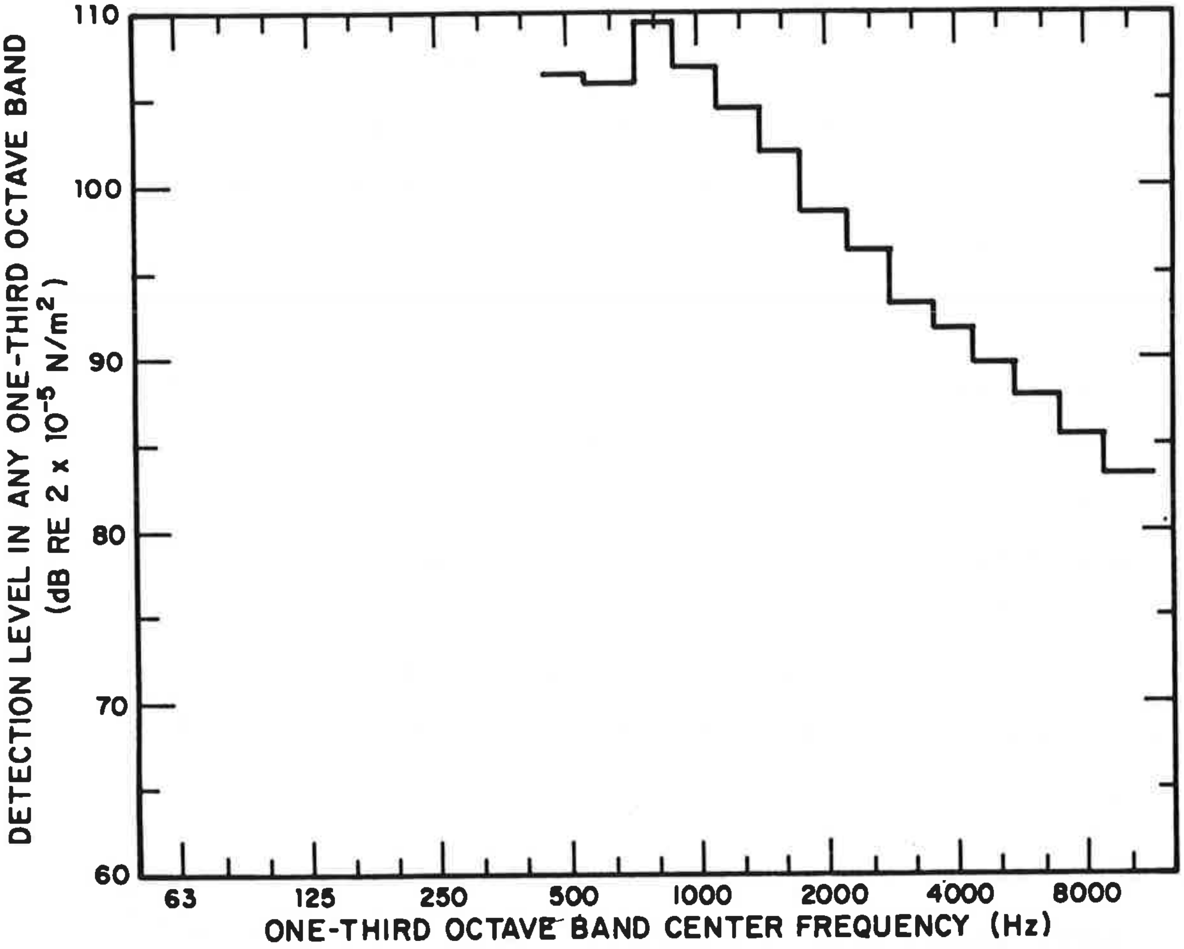

FIG. 38. SOUND PRESSURE LEVEL THAT MUST BE ACHIEVED IN ANY 1/3-OCTAVE BAND, IMMEDIATELY OUTSIDE THE RECEIVING VEHICLE IN ORDER FOR DETECTION TO OCCUR: RURAL MODEL, 55 MPH, RADIO ON, WINDOWS CLOSED.

the urban, suburban and rural situations selected here as representative.

Subtraction of the "required" spectra of Figs. 36-38 from the average siren spectra of 12 ft (3.6m) in Figs. 6-9 yields the maximum tolerable propagation losses for detectability. From this spectrum of tolerable propagation losses, the effectiveness distance can be conveyed. The results, which are given in Table 14, show the wide range of warning effectiveness distances for the model situations.

The greatest warning distance is possible in the suburban situation, as might be expected, since for this model the interior noise levels were the lowest and the insertion loss with the windows open is minimal. Even here, though, the greatest warning effectiveness distance (for the wail sound) is approximately 440 ft (134m), for the situation where the receiving vehicle is directly ahead of the emergency vehicle. Most typically, the warning effectiveness distances are 125 ft (38m) or less.

It must be emphasized that these calculated values are for a set of representative average situations; if the relevant properties of the sound, atmospheric propagation, and receiving vehicle change, the results could be different. However, these values do emphasize the extremely short warning distances within which drivers must clear a path for emergency vehicles.

TABLE 14. SUMMARY OF WARNING EFFECTIVENESS DISTANCES FOR REPRESENTATIVE SITUATIONS

URBAN SITUATION[1]

Source	Straight Ahead Distance Between Vehicles	Crossroads Distance Between Vehicles Developed Along Road
Electronic Wail	123 ft (37m)	39 ft (12m)
Electronic Yelp	120 ft (37m)	38 ft (12m)
Electronic Hi-Lo	81 ft (25m)	26 ft (8m)
Mechanical Wail	146 ft (44m)	40 ft (12m)

SUBURBAN SITUATION[2]

Source	Straight Ahead Distance Between Vehicles	Crossroads Distance to Corner
Electronic Wail	440 ft (134m)	>106 ft (32m)*
Electronic Yelp	426 ft (130m)	>106 ft (32m)*
Electronic Hi-Lo	257 ft (78m)	78 ft (24m)
Mechanical Wail	445 ft (136m)	>106 ft (32m)*

*Detected as vehicles emerge from behind assumed barrier.

RURAL SITUATION[3]

Source	Straight Ahead Distance Between Vehicles	Crossroads Distance to Corner
Electronic Wail	33 ft (10m)	14 ft (4.3m)
Electronic Yelp	32 ft (9.7m)	12 ft (3.5m)
Electronic Hi-Lo	24 ft (7.3m)	<12 ft (3.6m)
Mechanical Wail	33 ft (10m)	<12 ft (3.6m)

[1] Urban Traffic - Window Open - No Radio.

[2] 30 MPH - Window Open - No Radio.

[3] 55 MPH - Window Closed - Radio On.

The levels of siren sounds sufficient for detection and the 1/3-octave bands in which these levels occur just outside the receiving vehicle are listed in Table 15. These illustrate the high siren sound levels necessary, particularly when the radio is on.

There are several indications that the acoustic energy radiated by sirens at frequencies below 1000 Hz is not effective. When the shapes of the representative siren spectra (Figs. 6-9) are compared to the required signal level spectra (Figs. 36-38), it can be seen that detection might easily occur at frequencies of 1000 Hz and above. This fact is further emphasized by examination of the results in Table 14 for the hi-lo siren signal, which has a spectrum that peaks at a lower frequency than the other units examined (Fig. 8). It should be mentioned that these are representative model situations, but the results do suggest that the low frequency energy produced by present devices is largely wasted.

The detection of the wail and yelp signals occurs at the higher frequencies. Therefore, the longer cycling time of the wail signal can make it less effective as a warning, because during those periods while it is at the low end of its frequency range it will be less detectable. The yelp signal sounds more rapidly and so might be detected earlier. Increasing the frequency of the wail signal would counter this point.

TABLE 15. EXTERIOR SOUND LEVELS AND 1/3-OCTAVE BANDS AT WHICH DETECTION OCCURS IN MODEL SITUATIONS

Source	URBAN SITUATION[1]	
	Straight Ahead	Crossroads
Electronic Wail	90 dB/1600 Hz	90 dB/1600 Hz
Electronic Yelp	90 dB/1600 Hz	90 dB/1600 Hz
Electronic Hi-Lo	83 dB/3150 Hz	83 dB/3150 Hz
Mechanical Wail	87 dB/2000 Hz	87 dB/2000 Hz
	SUBURBAN SITUATION[2]	
	Straight Ahead	Crossroads
Electronic Wail	79 dB/1600 Hz	82 dB/1250 Hz
Electronic Yelp	79 dB/1600 Hz	82 dB/1250 Hz
Electronic Hi-Lo	72 dB/3150 Hz	83 dB/ 630 Hz
Mechanical Wail	76 dB/2000 Hz	82 dB/1250 Hz
	RURAL SITUATION[3]	
	Straight Ahead	Crossroads
Electronic Wail	102 dB/1600 Hz	105 dB/1250 Hz
Electronic Yelp	102 dB/1600 Hz	105 dB/1250 Hz
Electronic Hi-Lo	93 dB/3150 Hz	106 dB/ 630 Hz
Mechanical Wail	98 dB/2000 Hz	105 dB/1250 Hz

[1] Urban Traffic - Windows Open - No Radio

[2] 30 MPH - Windows Open - No Radio

[3] 55 MPH - Windows Shut - Radio On

Finally, it must be repeated that these examples are representative only; they do not necessarily apply to any given situation. They were developed to allow the characteristics of audible warning device detection to be studied. In the theoretical suburban situation, for instance, the warning effectiveness distance for the crossroads case is strictly controlled by the physical location of the assumed barrier. Yet suburban communities do not always have barriers of 75 ft (23m) from the corner, and they can have houses located at all distances, so the results are not generally applicable. They apply only to the model situation, a general representation of a suburban situation.

8. AUDIBLE WARNING DEVICES AND COMMUNITY NOISE LEVELS

8.1 EFFECTS OF NOISE ON PEOPLE

The commonly accepted effects of noise on people are:

- -> Annoyance
- -> Sleep disturbance
- -> Interference with speech communication, because noise masks speech sounds. (In noisy environments, talkers naturally raise their voices, or stand closer to their listeners to reduce this effect.)
- -> Temporary or even permanent hearing loss, when the noise is sufficiently intense and/or prolonged.

In communities, the sounds of sirens will probably result in annoyance and sleep disturbance. The exposure is too brief to affect speech communication, significantly or to produce hearing loss.

Data on the annoyance created by the sounds of emergency-vehicle sirens are sparse. One study [36] contains the interesting observation that "...sounds such as from sirens and horns evoke little annoyance in terms of either intensity or extensity." It was found that annoyance from exposure to sirens was reported primarily in a residential setting and that the annoyance may have been a by-product of sleep interference or interruption of mental activities. It was speculated that annoyance from such exposure was minimal, however, because of the widespread attitude that the use of sirens is proper, "legal," and necessary (beyond discretionary control). This favorable attitude toward the use of sirens probably stems from a general perception of emergency vehicles as "friendly"; that is, helpful and socially useful.

Corroboration of this viewpoint is found in a recent social survey conducted in seven American cities [37]. The goal of the survey was to examine the effects on nonaircraft and nonhighway noise exposure on the American public. More than 2,000 respondents were interviewed in various strata of noise exposure and lifestyles. Only 14 respondents, well under one percent, spontaneously mentioned sirens as highly annoying noise sources.

The results of these two studies suggest that nationally siren signals are not a major irritant. Undoubtedly, sirens do annoy a small number of the urban dwellers who are heavily exposed, such as those living along ambulance routes or by fire stations. No matter what steps are taken to alleviate the annoyance created by siren signals, this small proportion of the population could remain more heavily exposed than most. The issue thus becomes what measures may be taken to minimize this residual annoyance.

8.2 RATING NOISE IMPACT

There are many methods for rating, or quantifying, noise impact upon communities. One of the more popular rating scales, supported by the U.S. Environmental Protection Agency, is based upon the energy average of the fluctuating noise exposure over a typical time period [38]. This energy average, designated Leq [usually in dB(A)], is the level of a continuous sound that would have the same energy as the fluctuating noise exposure during the time period selected. For typical time periods on the order of a 24-hr day, siren noise exposures are generally too brief and rare to have a major effect on the Leq. Rather, the Leq would be determined by more common sounds, like motor vehicle traffic.

All noise rating scales, including those based upon Leq, take into consideration the following factors:

-> The magnitude of the noise intrusion, relative to the other sounds in the environment (i.e., the "ambient")

-> The spectral content of the noise intrusion, with particular emphasis on its tonal content

-> The duration, in frequency of occurrence of the intrusion

-> The time of day when the noise intrusion occurs

-> The season of the year when it occurs.

In all but the noisiest neighborhoods, the sound of a typical siren is well above that of the prevailing ambient noise level. Figure 39 shows the typical daytime "residual" noise

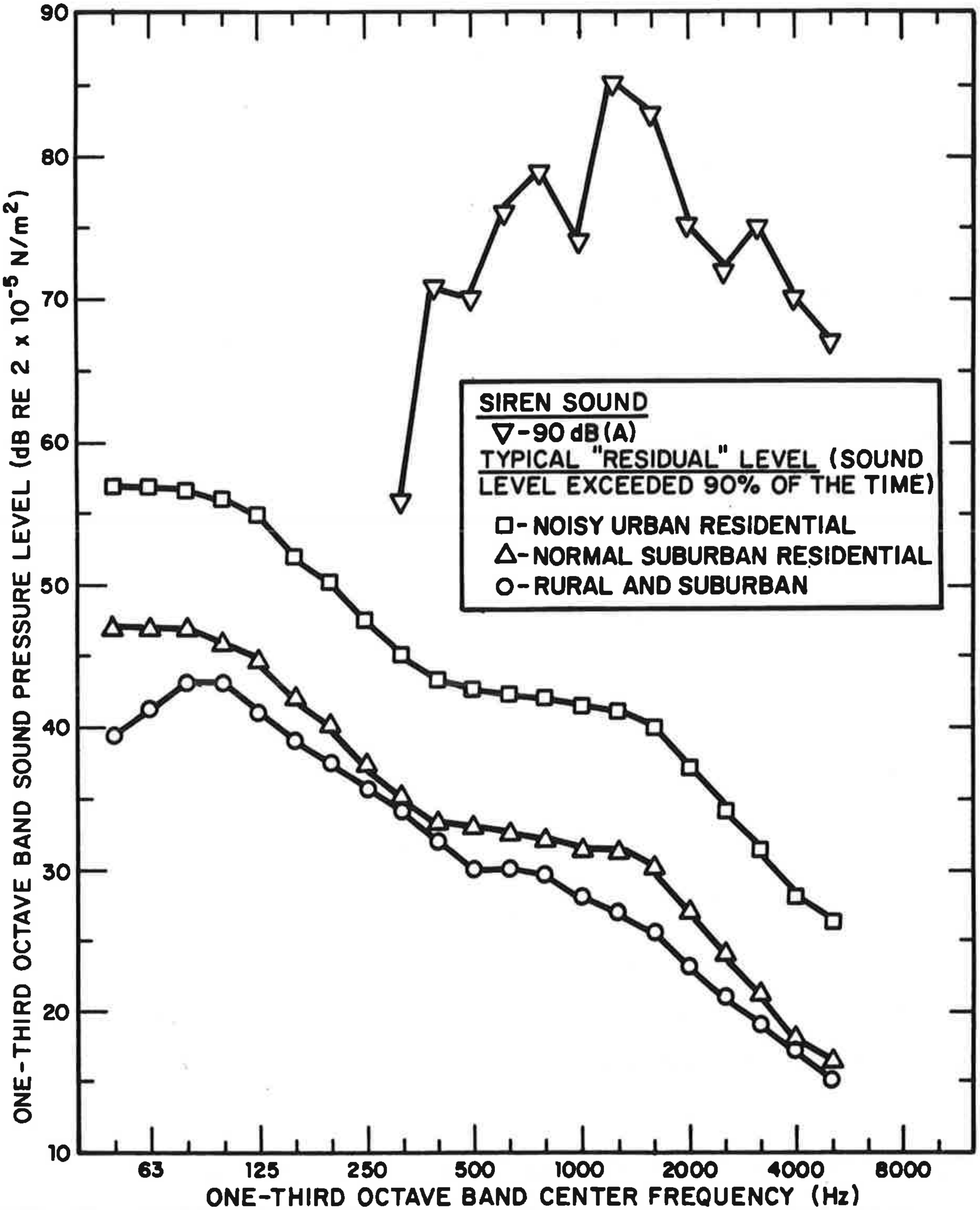

FIG. 39. SIREN SOUND COMPARED TO TYPICAL DAYTIME RESIDUAL NOISE LEVELS.

levels for three communities described as "Noisy Urban Residential", "Normal Suburban Residential," and "Rural and Quiet Suburban," respectively, by the US EPA [39]. Superimposed is the equivalent 90 dBA spectrum of a wail siren; it is obvious that the siren will be readily apparent to anyone subjected to this level. Indeed, any attempt to reduce the magnitude of the siren noise intrusion would also decrease its effectiveness as a warning device.

Tonal noises are generally considered to be more intrusive, and to produce more annoyance than broadband, nontonal sounds. However, reducing the tonal characteristic of siren sounds (in an effort to reduce their annoyance potential) would correspondingly reduce their effectiveness. Sirens are designed to be intrusive, to attract attention, and to be recognizable.

Because it is not generally practical to restrict the use of sirens to daytime periods only (when they could be less annoying), or to winter periods only (when home windows are usually closed), the only siren characteristic that can be adjusted to reduce annoyance without also reducing effectiveness is to reduce the duration and frequency of noise exposure. Two objectives are feasible in this regard:

1. To improve the directionality of sirens so that less sound energy is radiated directly to the sides and rear of the emergency vehicle (and above the vehicle). This would be easiest if the fundamental siren frequency was increased, which is also one of the reasons for increasing siren effectiveness.

2. To train emergency vehicle operators to restrict the use of sirens to situations where they might be effective, and to stop using them in situations where they are clearly ineffective (see Sec. 9).

9. CONCLUSIONS OF STUDY

9.1 ANALYSIS

This study of audible warning devices on emergency vehicles has shown the wide range of sound levels necessary to provide adequate aural warning for many potential situations. The results highlight the problems of providing sufficient audible warning with existing sirens and show that the warning distances are quite short, except under the quietest receiver conditions.

The key points demonstrated by this project are: the measured high level of interior noise in road vehicles at high speeds, especially with the radio operating, the uniformity of acoustical insertion loss of vehicle structures, the inability of drivers to localize siren directions in many situations, and the necessity for the sound levels of sirens to be approximately 10 dB higher than the detection levels in an ideal laboratory setting.

Logical deductions from the results of this study are that for existing siren systems, warning can be given effectively only to vehicles traveling in the same direction ahead of the emergency vehicle, to vehicles weaving slowly through dense stationary traffic, or to pedestrians. There is not much chance of warning drivers of those vehicles approaching head on, except under the most ideal situations. There is not sufficient warning to advise vehicles on converging roads. The attenuation of the sound in turning the corner in the urban situation and the high forward directivity of existing siren devices, coupled with the typical speed of the vehicles, in the rural situation can cause the warning distances to be too short for the receiving vehicle to brake and avoid a collision with an emergency vehicle which maintains speed.

One important conclusion that can be drawn from this study is that the mode of operation of the signal is not relevant to detection. The single most important measure is the short-term-energy-average signal-to-noise ratio at the listening driver's ear. For this reason, the use of alternative modes of operation and the development of new sounds is not indicated. In fact, new sounds might hamper the required response, because even when a sound has been detected, the listener must recognize the sound as that of an emergency vehicle. New types of sounds would require a program to educate the public.

9.2 SUGGESTIONS FOR THE IMPROVEMENT OF SIRENS

To be effective, the sound of a siren must exceed the background noise within a vehicle by about 10 dB. Typically, the background noise decreases at the higher frequencies by about 5 dB/octave (Fig. 26). The rate of decrease is even greater with the radio on. Thus, even though the vehicle insertion loss increases at a rate of about 2 dB/octave (Fig. 16, with windows closed), a 3-dB/octave improvement in effectiveness could be achieved by increasing the frequency of maximum sound output of sirens. This is true up to that frequency where the molecular absorption of sound in the atmosphere would more than compensate for the 3-dB/octave gain. Thus, if the frequency of maximum siren sound output were increased from 1250 Hz (typically) to 3150 Hz, the effective signal level would be increased by about 4 dB for nearby listeners and by about 2 dB for listeners 500 ft away. According to the model developed in Sec. 7, the warning effectiveness distances would increase by about 40%.

To improve the effectiveness of sirens in warning devices on cross streets, the siren directivity should be more uniform in the forward quadrant (i.e., within ±45 degrees of the straight-ahead direction).

It is obvious that increasing the sound level of sirens would improve their effectiveness. However, it is clear from Sec. 8 that increasing the siren sound level, like most other siren properties that could be altered to improve siren effectiveness, would also increase the siren's community annoyance potential. The only two means of reducing siren annoyance potential are:

-> Changing the directivity of sirens so that the radiation of sound directly to the sides and to the rear of the emergency vehicle is minimized,

-> Training emergency vehicle operators not to use sirens when they are unlikely to be effective.

9.3 SUGGESTIONS FOR THE TRAINING OF EMERGENCY-VEHICLE DRIVERS

Some states already publish handbooks for emergency-vehicle drivers that contain recommendations for the use of sirens, but most of them do not recognize some of the points uncovered by this study. For example, it is often implied that the location of an emergency vehicle can be detected by its siren sound and that changing the mode of operation of the signal can help in attracting attention to the siren. The results of the experiments reported here have shown that this information is not generally true.

The results of this study, could be the basis for a handbook and a training course for emergency-vehicle operators that would emphasize:

-> The physical parameters that establish the effectiveness of sirens: sound level and spectral content, directivity, propagation losses, vehicle insertion loss, and vehicle background noise level.

-> The inability of drivers to detect siren sounds within a safe distance under some conditions, particularly at crossroads.

-> The inability of drivers to localize the source of siren sounds under many conditions.

-> The necessity to restrict the use of sirens to situations where their effectiveness is most obvious: warning of pedestrians and slow-speed, low-background noise situations.

-> The necessity for driving an emergency vehicle with the presumption that some drivers may not hear a siren within a distance sufficient to take safe evasive action.

Training programs for the use of sirens should include practical examples of siren use to demonstrate these points. Drivers of emergency vehicles should be instructed not to rely on their sirens, but to watch for the reaction of other vehicles to the sirens and be prepared to maneuver accordingly.

9.4 SUGGESTIONS FOR THE REGULATION AND STANDARDIZATION OF SIRENS

Industry standards, recommended practices, and regulations regarding sirens could be directed in two areas: (1) measurement of siren <u>performance</u> in a manner related to siren effectiveness, to allow rank-ordering of the effectiveness of different sirens or to establish compliance with minimum performance requirements and (2) restriction of the <u>use</u> of sirens to situations where they would be most effective, to minimize community annoyance. The second objective - control of siren use - has already been discussed.

Present methods for measuring siren performance in terms of so many dB(A) at a specified distance in front of the sirens miss many of the features important to the effectiveness of sirens. It would be possible to use the results of this study to develop a measurement procedure and rating scale for rank-ordering the effectiveness of sirens on the basis of physical observations. Such a procedure could be developed as follows:

1) Add the insertion loss results from Fig. 16 (with windows closed) to appropriate background noise spectra from Fig. 26. Then add 10 dB to obtain the required signal level for detectability just outside a receiving vehicle. The result of this process will be threshold spectra like those illustrated in Figs. 36-38.

2) Measure the short-term, energy-average 1/3-octave band sound level of the candidate sirens on-axis and ± 45 degrees from the forward direction. These measurements should be made with a representative operating configuration, and at a convenient radial distance from the siren. The results would be similar to those illustrated in Figs. 6-9.

3) Subtract the chosen spectrum obtained in step (1) from the spectra measured in step (2). Select that 1/3-octave band where the difference is most positive for each siren and rank that siren in direct proportion to the magnitude of the difference in that 1/3-octave band.

   This ranking could be done separately for the on-axis siren measurement and for the measurements at ±45 degrees from the forward axis. The three separate rankings thus obtained could be averaged to yield a simple effectiveness rating number for each siren.

In a similar way, a rating that describes the community noise impact and potential for annoyance of sirens could be developed from the differences between siren spectra and selected community noise spectra, with consideration given to the desirability of reducing siren noise radiation to the sides and rear of emergency vehicles.

10. RECOMMENDATIONS

On the basis of this study, the following recommendations are made for increasing the effectiveness of sirens:

1. Increase the level of sound produced.
2. Provide uniform radiation in the quadrant within ±45 degrees of the forward direction and minimize radiation in all other directions.
3. Increase the frequency of maximum siren sound output to the vicinity of 3000 Hz.
4. Provide training manuals and courses for emergency-vehicle operators that emphasize the real properties and limitations of sirens.
5. Restrict the use of sirens to situations where they are clearly effective.
6. Develop a standardized method for rank-ordering the relative effectiveness of sirens on the basis of physical measurements.
7. Realize that sirens will never become a generally effective warning device without also becoming an intolerable community noise problem. Order-of-magnitude improvements in future warning effectiveness will have to be based upon nonauditory means.

APPENDIX

BBN SIREN DIRECTIVITY MEASUREMENTS AT VARIOUS ANGLES AT 3.6 M DISTANCES

MAX dB(A)/L_{eq}

Type	Front	45° R	90° R	135° R	180° R
Fed. PA200 w/cp 25 Speaker; wail	125.0/118.3	119.4/111.2	114.7/102.4	112.2/101.8	116.4/108.6
Fed. PA200 w/cp 25 Speaker; yelp	121.0/118.0	114.2/111.1	108.6/105.2	107.2/104.3	111.8/108.8
Fed. PA200 w/cp 25 Speaker; Hi-LO	114.0/110.7	113.5/109.9	107.4/104.1	106.8/103.7	110.3/107.1
Fed. PA200 w/cp 100 Speaker; Wail	127.5/120.8	*/113.6	*		
Fed. PA200 w/cp 100 Speaker; Yelp	123.4/120.5	/113.0			
Fed. PA200 w/cp 100 Speaker; HI-LO	118.2/115.0	/114.0			
D-N Unitrol 800 w/atlas HPR 370 Speaker; Wail	127.6/120.1	/113.0			
D-N Uni 880 w/atlas HPR 370 Speaker; Yelp	121.6/119.6	/113.0			
D-N Uni 800 w/atlas HPR 370 Speaker; Hi-LO	115.9/113.2	/110.7			
Carson SA410 w/390R Speaker; Yelp	121.9/119.4	/115.2			
Carson SA 410 w/390R Speaker; Wail	124.8/118.9	/115.0			

BBN SIREN DIRECTIVITY MEASUREMENTS AT VARIOUS ANGLES AT 3.6 M DISTANCES

MAX dB(A)/L_{eq}

Type	Front	45° R	90° R	135° R	180° R
Carson SA 410 w/390R Speaker; Hi-LO	117.8/114.8	/111.5			
Carson SA310 w/390R Speaker; Wail	121.1/113.1	/108.4			
Carson SA310 w/390R Speaker; Yelp	115.9/113.3	/109.1			
Carson SA310 w/390R Speaker; Hi-LO	117.2/114				
B&M S8/ Electro-mechanical Wail (on-off 5SEC.)	121.8/115.5				
B&M S8/ Electro-mechanical Wail (on-off 5 Sec.)	121.3/115.7				
B&M S8/ Electro-mechanical Wail (continuous)	120.6/119.7				

* Where Max dB(A) and/or Leq is not tabulated data was not reduced for tapes.

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REPORT OF INVENTIONS

Work performed under this contract examined the effectiveness of audible warning devices on emergency vehicles by measuring their aural detectability. Although this study has yielded a substantial body of valuable data which significantly extends existing scientific knowledge, a diligent review of the work performed under this contract has revealed no innovation, discovery, improvement, or invention.

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