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Sixteen drivers (eight under 30, eight over 60) drove a moderate fidelity driving simulator at approximately 45 mi/hr while performing a three-choice response-time task simulating use of an in-vehicle system. All driving was on two-lane roads with no traffic. There were no headwinds or any variations in drag, so maintaining a constant speed was extremely easy. Driving occurred under three conditions--no sound, speed-related sounds only (engine, drive train, and wind noise), and all sounds (speed sounds plus tire squeal and shoulder sounds).

The type of sounds provided (or their absence) had no significant effect on response time. In terms of driving performance, providing sound caused drivers to decrease their mean speed by 1-2 mi/hr and to reduce the variability in their speed, though these differences were not statistically significant. Providing sound had no significant effect on either mean (or standard deviation) of lateral position, though subjects tended to drive closer to the center of the lane when shoulder sound was provided. In contrast, conditions in which no sound was provided were rated as just as realistic as when sound was provided.

These data suggest that the benefits of speed-related sounds are relatively small for nonchallenging human-performance experiments conducted in driving simulators where speed maintenance is of interest. The development of high-fidelity sound systems cannot be justified for that purpose.

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INTRODUCTION

The Driver Interface Research Simulator is being developed as a tool for basic and applied research on driving and safety. The simulator is being used to study workload and fatigue, the effects of alcohol and disability due to disease and aging, and the safety implications of new in-vehicle technology such as cellular phones and touch-screen interfaces. These studies are of particular interest to the federal and state governments, vehicle manufacturers, parts suppliers, automotive researchers, and others.

Research Objectives

At the outset of the project it was believed to be important to accurately represent vehicle sounds in a driving simulator so that driving performance in the simulator would match on-the-road performance. To examine that belief, a sound module was added to the driving simulator and an experiment to assess its benefits was conducted.

This experiment examined the following issues:

1. Does the presence or absence of sound affect driving performance?

2. Does the presence or absence of sound affect the sense of driving realism as perceived by drivers?

3. Do maneuver-related sounds affect driving performance?

To provide guidance, a limited literature review was completed at the outset of this project. Research pertaining to this experiment concerns four topics: (1) specific studies addressing the relationship between sound quality and driving simulator fidelity, (2) basic research on speed estimation, (3) studies concerning the effects of interior sound levels on communication interference, and (4) more general studies concerned with vehicle sound quality as it affects product perception. Descriptions of studies that pertain to each topic follow.

Research on Sound Cues and Simulator Fidelity

The authors have identified only one previous experiment directly addressing the effect of the presence or absence of sound on driver performance in a simulator. McLane and Wierwille (1975) examined that issue and the importance of motion cues in the Virginia Tech driving simulator. The audio cues included a stereo recording of aerodynamic and chassis sounds, along with a speed-dependent sound for engine and drive-train noise. Forty-eight drivers operated the simulator under one of six conditions across which motion (with and without roll, yaw, translation) and audio cues (with and without) varied. Each test block was nine minutes long. Performance measures included the number of steering wheel reversals (>3.4 degrees), the number of accelerator pedal reversals (>3% full travel), the mean yaw deviation, the mean lateral deviation, and the mean speed deviation.

Relative to the control condition (all motion and sound cues present), eliminating engine noise had relatively small effects on lateral control (4% change in steering wheel reversals, 1% change in lateral deviation) but moderate effects on speed control (19% change in accelerator reversals, 27% change in velocity deviation). This research demonstrated the need for speed-related sound cues where speed control is important. However, those cues had no impact on lateral control.

Research on Sound and Speed Perception

Given that the likely effect of providing sound will be on speed control, not lateral position control, how well do people estimate speed? Evans (1970a) obtained estimates of speed from 18 passengers while riding normally, wearing blindfolds, wearing ear muffs, or wearing both blindfolds and ear muffs in vehicles whose speedometer was covered. Speeds driven were from 10 to 60 mi/hr. The test vehicle was a 1967 Chevrolet Impala driven with the air conditioning on. Subjects tended to underestimate the speed being driven, especially when the driven speed was 25 mi/hr or less. The absolute amount of the error increased with speed. The mean estimated speed was 1.6 mi/hr less than the actual speed when all senses were available, 0.7 mi/hr above actual when vision was unavailable, and 4.7 mi/hr below the actual when hearing was unavailable and 5.7 mi/hr below the actual when both hearing and sight were unavailable. This suggests that hearing was more important than vision in absolutely estimating speed, and that depending on the speed, speed control errors could be large if speed-related sounds are not provided.

In a subsequent experiment, Evans (1970b) had 70 subjects watch films of 15 road scenes, and then estimate the speed driven. Data from the front of the room (where the visual angle was identical to the real world), closely resembled the data from the diminished hearing condition from the on-road experiment. This situation also closely resembles that found in a fixed-base driving simulator with the sound turned off.

Research on Sound Presentation Methods In Simulators

Nelson and Nilsson (1990) examined whether the device used to deliver music to drivers, (speakers from standard in-vehicle entertainment units or headphones from Walkman-type stereo units), interfered to different degrees with driving. Twelve people drove the University of Alberta's simulator while listening to music of their own choosing presented at 63 dB. The road scene was a recorded video image that was shifted laterally depending upon the steering input from the driver. Speed feedback was provided by an LED that responded to the depression of the accelerator. The desired throttle position varied. Sound feedback was provided by two motors that could be turned on (95 dB grating sound, 78 dB whining sound) to indicate the engine was lugging or over-revving. Various sounds were presented to cue drivers to brake (96 dB sound-rough road shaker), close the window (65 dB staccato sound for gravel), shut off the engine (86 dB overheat alarm), and restart it (75 dB white noise). Frequency spectra for the various sounds were not provided.

Tasks in the two three-hour test sessions included adjusting speed (13 times), shifting gears (6 times), applying the brakes, operating a window control, and starting and stopping the engine. Subjective assessments of fatigue were obtained every 45 minutes.

There were no differences in subjective levels of fatigue due to presentation method. Response time to shifting gears was approximately 1/3 second longer when headphones were worn (a 15% increase), and the difference was statistically significant. This complex task relied upon auditory cues, suggesting to the authors that headphones may interfere with drivers responding to external sounds, some of which could be safety related. There were also nonsignificant increases in steering error and reaction time to occasional hazards, performance measures of tasks that rely upon visual input, and physical symptoms of fatigue.

One potential implication is that headphones may not be the best choice for presenting simulator sounds in some cases. Headphones require much less equipment, less attention to room acoustics, and offer less disturbance to those in spaces adjacent to a simulator. If headphones are used, then all sounds need to be presented through the headphones and levels need to be adjusted to the match the levels at which they would be heard if delivered via speakers.

Research on Sound Quality Perception In Simulators

Musical Instrument Data Interface (MIDI) systems are often used for sound quality evaluations. However, providing a sophisticated MIDI system with studio-quality mixers, speakers, and amplifiers is inconsistent with the concept of a low-cost driving simulator. It is therefore important to understand which sounds need to be simulated (and how realistically) to provide the necessary auditory feedback to drivers.

Fujita, Nishiyama, and Hayakawa (1988) describe an effort to identify the "sporty feeling of exhaust noise." They had 20 male sound experts rate the exhaust sounds from 9 cars on 7 bipolar adjective scales (drawn from a set of 20). Three driving conditions were examined (acceleration and deceleration in first gear, shifting up from first to third) in four different ways (speaker reproduction, semi-anechoic chamber, output corrected with a graphic equalizer, and sound pressure levels equalized). A multidimensional scaling analysis revealed two dominant quality factors, "powerful" and "buoyant" (not straining as rpm increased) The perception of these qualities was most closely related to the second harmonic of due to engine rotation, and to a lesser degree to the fourth and eighth harmonics.

Figure 1 shows the change in the engine harmonic as a function of engine speed. Figure 2 shows the spectral distribution for 2000 rpm. Figure 3 shows the relationship between the perception of power and the decrease in the overall sound intensity as engine speed increases above 2000 rpm.

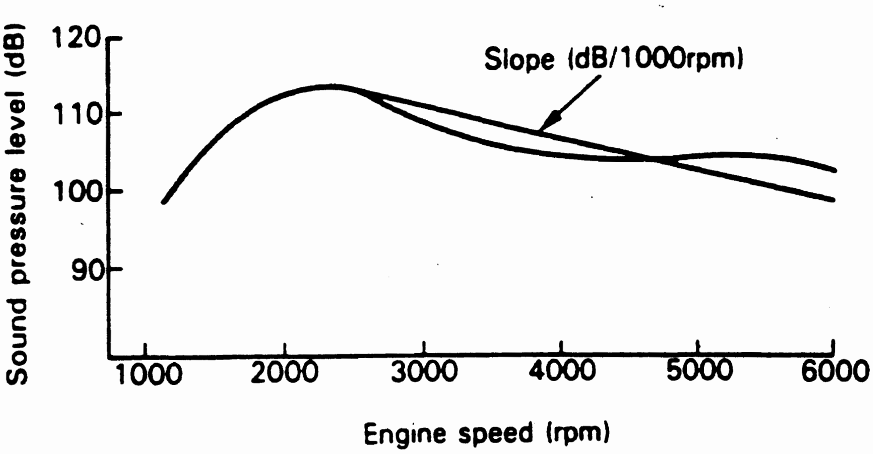


Figure 1. Change in second harmonic of engine speed

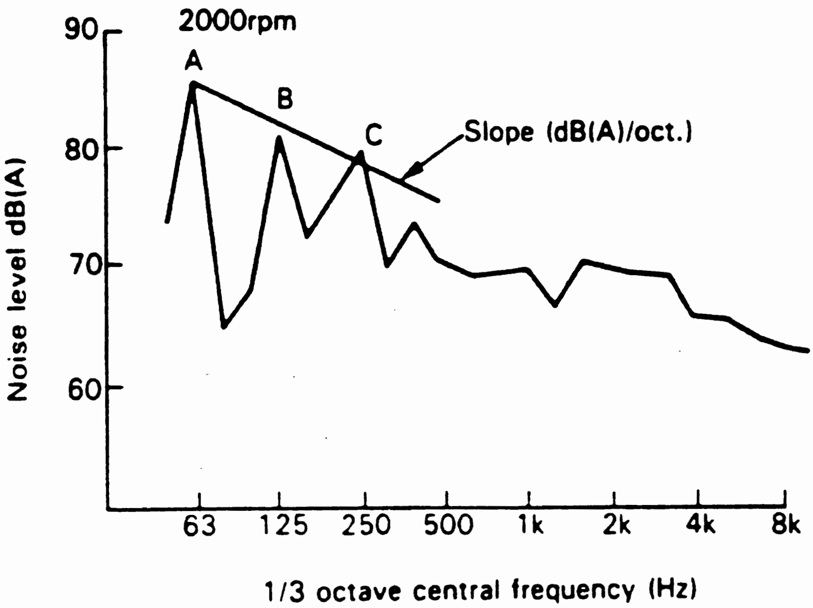


Figure 2. Frequency spectrum at 2000 rpm

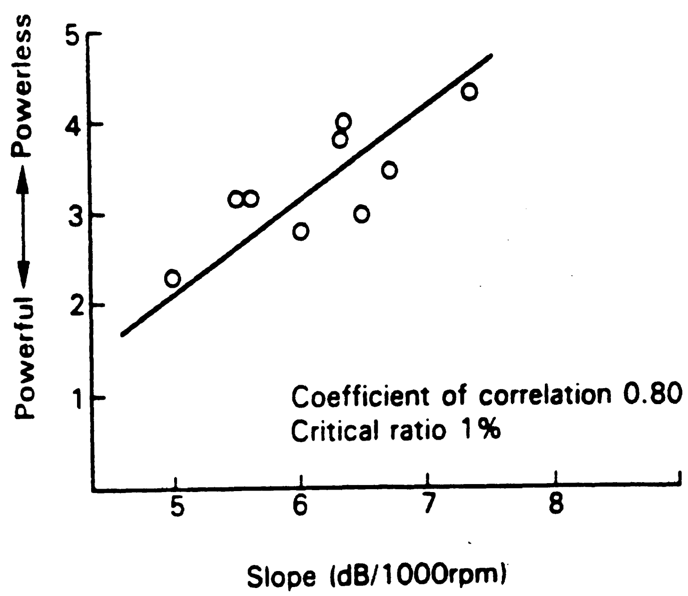


Figure 3. Effect of slope of second harmonic on ratings of powerfulness

One interpretation of the results is that it may be sufficient to represent only the harmonics of engine-related sounds in a simulator, not the entire spectrum. Further, altering the relationship of the harmonic peaks has a strong influence upon the perception of sound by a driver, and by extension, possibly the perception of speed.

Okamoto, Furugoori, Hirahata, Abe, and Hata (1991) describe a system for processing and presenting vehicle sounds. Thirty-one people were presented with sounds from 4 vehicles and rated them on 7 bipolar adjective scales. They did this by operating an accelerator to generate sounds and by passive listening to tapes. A factor analysis of the data from each method led to emphasizing different factors, with "responsiveness" being apparent in the accelerator operation method, suggesting that a driving simulator, and not passive listening is preferred for sound-quality evaluations. It seems reasonable to suggest that it is not necessary that such a simulator provide a high-quality visual scene.

In a related study of vehicle sounds during acceleration, Yagihashi (1991) groups sounds that occur into five categories based on driver impressions--rumble, muddiness, roaring, booming, and nonlinear sounds. Muddiness is the discordant, unpleasant sounds heard when harmonics of two more pure tones of 2n+/-1 become mixed. Roaring noise is the sound heard at high speed that gives the impression the engine is about to break down. It is strongly associated with primarily the second and, to some extent, fourth-order harmonics (200-300 Hz, 350-550 Hz) of engine noise. Booming noise tends to be associated with low frequency (25-160 Hz) sounds associated with fairly pure tones. The perception of booming noise was greatest in the vicinity of 120 Hz. Nonlinear sounds are noises of varying origin that suddenly rise during acceleration. The lesson learned from this work is that simulations of vehicle sounds should focus on low frequencies.

Research on Sound Interference with Communication

Gilloire, Lockwood, and Boudy (1992) discuss issues related to hearing speech in vehicles. While their paper emphasizes methods for enhancing the speech signal, they also discuss the background sounds, a topic of interest to this research. They identify the main sound sources as being vibration due to engine rotation transmitted through the chassis and body, tire noise (which is specific to the tire, road material, and road covering [rain, snow]), and aerodynamic noises. The design of the passenger compartment has a significant effect on the nature of the sounds occupants hear. Figure 4 shows a sound spectrum (reportedly typical) for which the vehicle, tires, and road conditions are unspecified. Most of the sound energy is below 250 Hz, though there is a moderate presence up to 750 Hz.

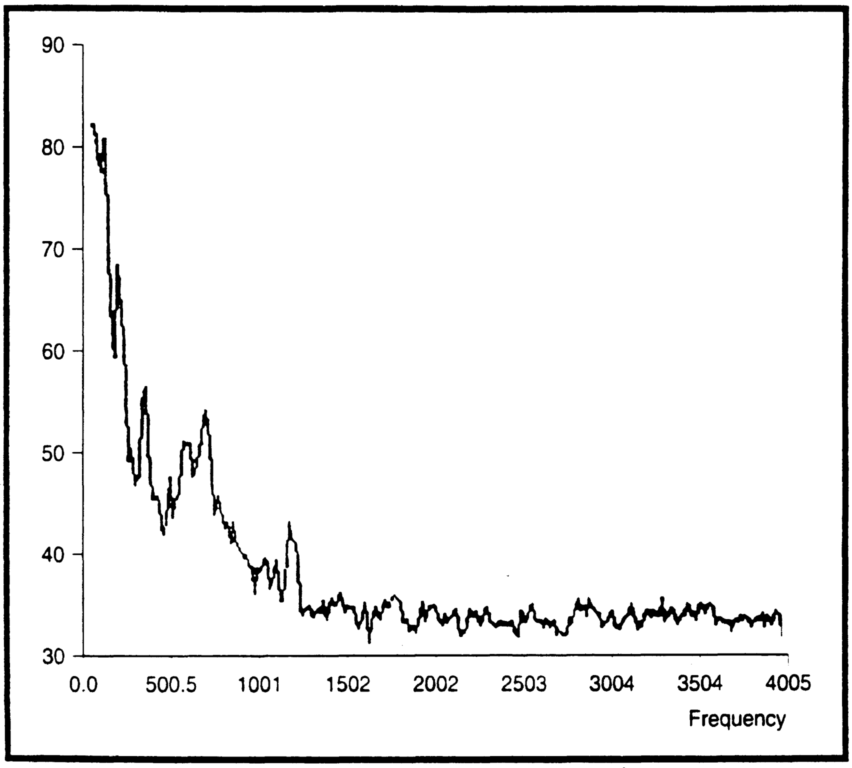


Figure 4. Spectrum of ambient noise in a passenger compartment (dB)

As a group, these studies suggest that providing sound does affect the perception of speed, and may have a small effect on speed maintenance. Sounds that should be presented are primarily low frequency. Of interest was how repeatable these findings were and if these findings applied to the driving simulators being developed at UMTRI.

TEST PLAN

Driving Simulator

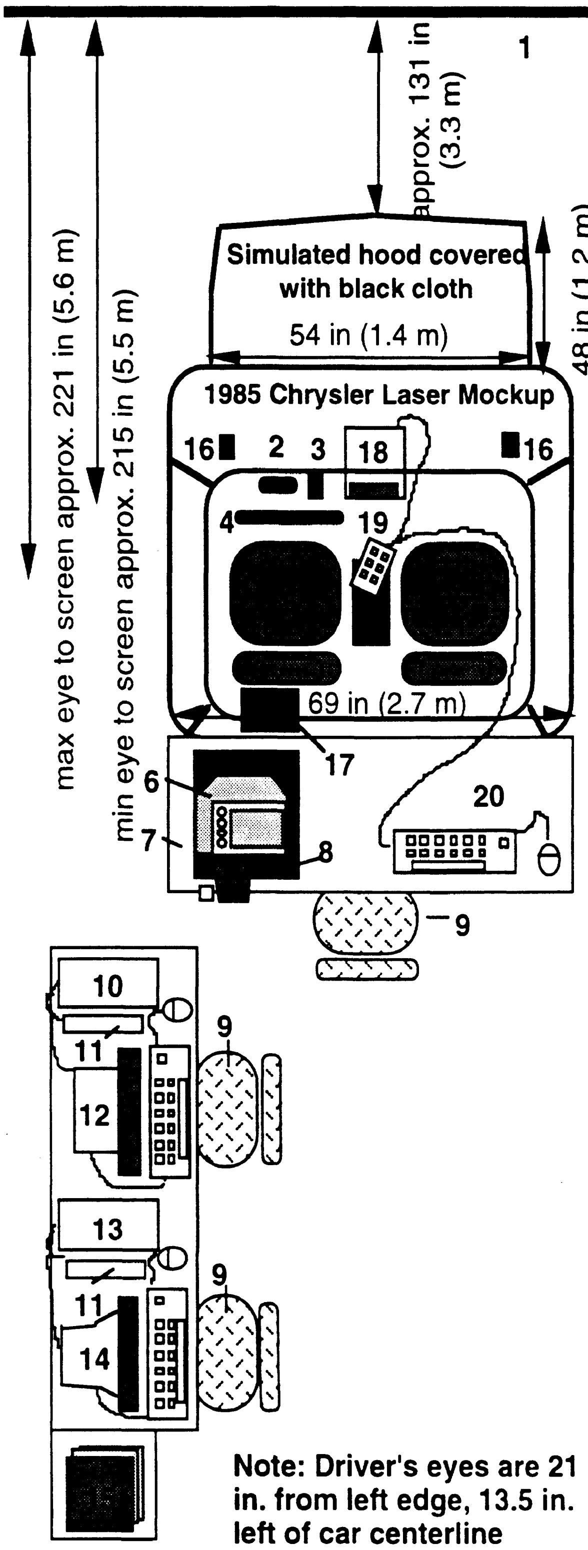
Data was collected using the UMTRI Driver Interface Research Simulator (MacAdam, Green, and Reed, 1993). When this experiment was conducted, the simulator consisted of two Macintosh computers (one to control the experiment and generate the road scene, a second for sound) linked via AppleTalk, an LCD panel and overhead projector (to show the scene on a reflective wall), and a left-hand-drive vehicle mockup with a working steering wheel, foot controls, and a speedometer. This equipment is shown in Figure 5.

The simulator was housed at one end of a 15 ft x 75 ft room. The room was somewhat reverberant (tile over concrete floor, concrete ceiling, plasterboard walls one of which was partially covered with carpet). Sounds were generated using high quality, consumer grade audio equipment (Kenwood receiver and graphic equalizer, JBL speakers mounted in the dash, JBL subwoofer below the vehicle).

The simulated vehicle weighed 3215 lb (7073 kg, split 43/57 among the front and rear wheels) and had an 8.4 ft (2.6 m) wheel base. The front and rear cornering stiffness were 150 lb/deg and 225 lb/deg, respectively. The yaw inertia was 1500 slug-ft^2. The driver eye height was set at 42 in (1.1 m). Steering resistance was provided by springs attached to the steering column.

The screen update rate depended on the number of objects in the scene and the sight distance specified. Rates of 15-20 Hz were common, with the range being 10-30 Hz. Data recorded each time the screen updated included throttle position, steering angle, vehicle speed, position in lane, vehicle yaw, road heading, vehicle heading, elapsed time, and distance traveled.

The custom-developed simulator software was written in MetroWerks C. Similar versions of the software are used on a development system in the Human Factors Division, in versions used by the BioSciences Division (for studies of seat comfort) and Engineering Research Division (for studies of on-center handling).



1 - Free-standing wall covered with 3M hi-white encapsulated reflective sheeting(8X12 ft)
2 - Brake pedal
3 - Accelerator
4 - Steering wheel
5 - Car seat
6 - Sharp model QA-1650 LCD computer projection panel
7 - Custom stand for projector
8 - 3M model 9000 RJH overhead projector
9 - Experimenter's seat
10 - Macintosh Quadra 840 AV Computer with Apple extended keyboard II and Apple Desktop Bus Mouse II
11 - Bernoulli model B190TM 90MB Mac transportable drive
12 - Macintosh model M1212 13" Color Display
13 - Power Macintosh 8100/80AV Computer with Apple extended keyboard II and Apple Desktop Bus Mouse II
14 - Apple model M2943 15" Mulltiple Scan Display
15 - Audio generation equipment Kenwood model KX-48C stereo cassette deck; Kenwood model KR-A4060 AM-FM stereo reciever; Kenwood model GE-7030 stereo graphic equalizer
16 - JBL Micro High Frequency Satellite Speakers
17 - JBL SB Micro Low Frequency Companion Speaker
18 - Apple Macintosh SE computer
19 - Kensington NoteBook KeyPad
20 - Apple extended keyboard II and Apple Desktop Bus Mouse II

Figure 5: The UMTRI Driving Simulator

Simulator Enhancements

To conduct the sound experiment, several modifications were made to the simulator. These included porting the simulator to the PowerPC platform (so as to allow use of current computer hardware), distributing the processing of the simulation across a network (to avoid processor overload), adding a numeric speedometer, adding routines to generate sound (as a function of engine rpm, vehicle speed, and engine load), and other minor enhancements. The code improvements and hardware upgrades provided a side benefit of increased frame rate (and realism).

Test Roads

Three simulated two-lane road sequences were created specifically for this experiment, and were designed such that the workload for all roads were equivalent as estimated by Wierwille's model (Hulse, Dingus, Fischer, and Wierwille, 1989; Green, Lin, and Bagian, 1993). In computing total workload, it was assumed the workload contribution of each road segment should be proportional to its length (road segment length divided by total road length). Each of the three road sequences was composed of five segments. The first section was driven during the warm-up phase of the experiment. A stop sign on the shoulder in the last segment indicated completion of the experiment. Data collected from subjects for both of these segments was ignored.

The middle three segments were each designed to correspond with the three phases of data collection for each road: a 4-minute drive at 45 mi/hr, a 4-minute drive at 45 mi/hr with the reaction task operating, and a 4-minute drive at the subject's personal, fastest, comfortable speed while concurrently completing a response-time task.

The estimated workloads for the three data-collection segments are similar, as all roads have similar proportions of curves and straight sections, and equal curve radii. A sample of one version of segments 1 and 2 had 45 sections -- 20 straight sections (150 to 870 ft long), 11 right curves (500 to 1500 ft radius) and 14 left curves (500-1500 ft radius). Segment 3 had 75 sections (35 straight sections, 18 right curves, 22 left) with approximately the same range of lengths and radii. All lanes were 12-ft wide. There were no intersections and no traffic. Road segments had signs, trees, posts, and other objects next to them, generally some distance from the road. Road characteristics that were specified include the heading and slope of each 30-ft (9.1 m) segment. Details on the roads appear in the appendix. Table 1 shows how segments were grouped.

Table 1. Road segment grouping

	Road Sequence		
Segment	1	2	3
warm-up	w	wa	wb
1	1	1a	1b
2	2	2a	2b
3	3	3a	3b
end	e	e	e

Note: All versions of roads, for example road 1, are mirror images of each other, with slightly different beginnings and ends (typically the first few hundred feet) so that segments blend into each other.

A sample image shown to the driver appears in Figure 6.

Figure 6. A sample road section.

Sounds Presented

The sound samples used to create the sounds presented by the simulator were drawn from a set of twelve 5-to-10-second samples gathered from various sources. A complete set of sound spectra appears in the appendix. The sounds appear to be reasonable for those typical of vehicles, though the tire sounds have slightly less low-frequency energy than is reported in the literature (Nelson, 1987).

The sound samples included engine sounds at 850, 1350, 2030, 2700, 3470, 4230, 4920, and 5710 rpm; wind sound; normal road/tire sound; tire squeal; and a shoulder sound used to indicate that the vehicle was past the road edge. The engine sound recordings were obtained from a late model Chrysler LH full-size sedan on a dynamometer in an anechoic chamber. The dynamometer was connected directly to the axles of the vehicle to remove wheel noise from the sound sample. In this configuration, the engine was held at a steady rpm reading and the sounds were collected. The only component to these samples therefore was the sound emanating from the power train of the vehicle.

For wind and road sounds, judgments from members of the research team were used to select candidates for use in the simulation. The road noise was mixed from various sound samples including sounds recorded on a driving course. The wind noise was mixed from sound samples received from Chrysler, sound samples were gathered in an UMTRI vehicle, and sound samples were created using a fan.

The quality of the tire-squeal and shoulder sounds was not considered to be critical. The tire-squeal sound was copied from a sound resource on an earlier version of the driving simulator used by the UMTRI Engineering Research Division. (It had been created by driving a car in a tight circle and recording the squeal with an ordinary tape recorder.) The shoulder sound was generated by mixing a variety of sounds from Chrysler with sounds gathered by the Engineering Research Division.

All sounds were presented in such a manner that, taken together, they form a representative ensemble for the simulator at each particular moment. Of the 12 sound samples, only 6 were active at any time. This reduced the possible load on the computer generating the ensemble such that the machine was able to maintain all sounds at peak load. For each particular engine rpm, the appropriate engine sound was generated by linearly cross-fading between the nearest pair of sounds (one frequency setting above, one below) for which a sample existed. (See Figures 7 and 8.) Specifically, when the simulator model rpm value is exactly at an rpm value for which an engine sound sample is available (for instance 2030 rpm) this sample is being played at 100% volume and 100% playback rate, while the other sample is at 0% volume. As the rpm ramps up toward 2700 rpm, the volume on the 2030 rpm sample decreases, and the rate increases from 100% upwards to a rate corresponding to 2700 rpm. Simultaneously, the volume on the 2700 rpm sample increases from 0% to 100% volume while the rate of this sample also ramps upwards from a value corresponding to 2030 rpm towards the standard 100% playback rate, which will be achieved when the simulator reaches 2700 RPM. Other alternatives besides linear transition were explored for this cross-fading scheme, such as using exponential curves in the transition regions shown in the two figures. However, it was determined subjectively that the linear transitions were the smoothest in the rise from idle to full throttle.

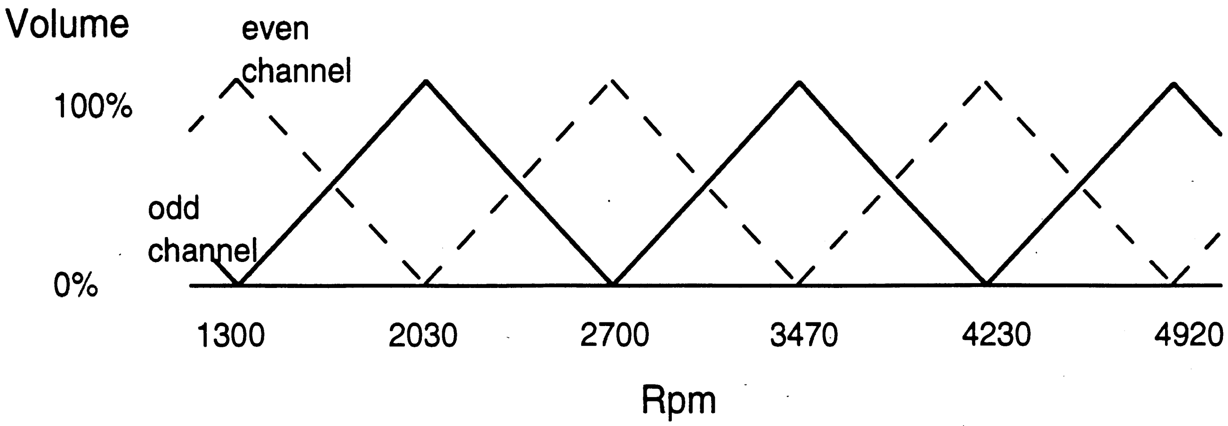


Figure 7. Cross-fading channel weights.

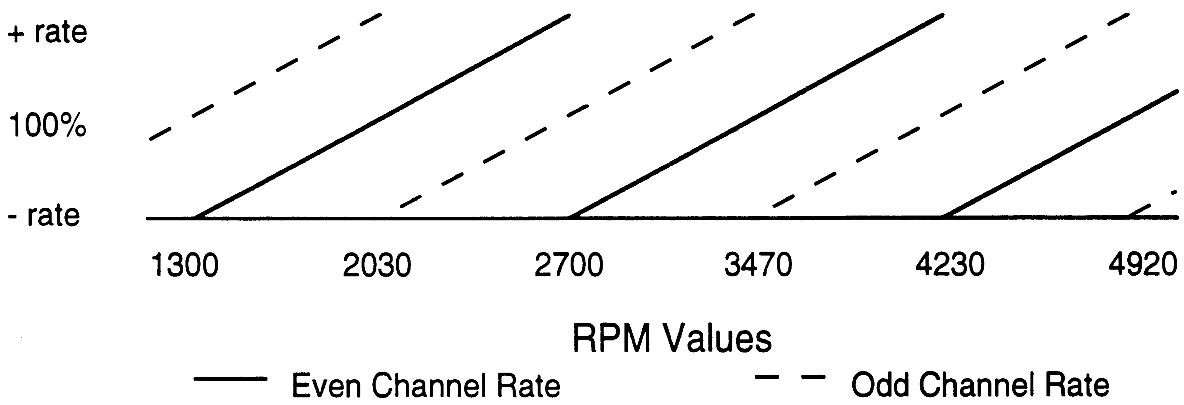


Figure 8. Cross-fading algorithm rates.

During the debugging phases, some tuning of the play rate of the sound samples was required based on subjective evaluations. The addition of a transmission to the vehicle dynamics models was required to simulate the sounds generated by the upshifting and downshifting of a transmission. These transmission noises are then reflected in the engine noise variations due to rapid RPM transitions generated when a shift occurs. Given that the sound presentation code is developed, replacing the sound resources with sounds for another engine/drive-train/tire package should be straightforward.

To determine how loud sounds were to drivers, typical sound levels were measured using a Quest model 2800 sound level meter held at a location near the center of a driver's head for a midrange seating position. (See Table 2.) The amplifier levels were set to values that seemed reasonable in the simulator. (They correspond to a setting of "4" on the amplifier volume.) It should be emphasized that the perception of sound is more important than reality, and therefore it may be desirable to have sounds played back at levels greater than those typically found in cars.

Table 2. Sound levels at driver's ears.

Source	Level (dbA)
background (computers and electronics on, car stationary)	46
driving at 35 mi/hr	60
driving at 45 mi/hr	61
driving at 55 mi/hr	63
45 mi/hr wind only	51
45 mi/hr tire/road noise only	57
45 mi/hr engine noise only	56
tire sounds (squeal)	48
off-road sound	62

Other Equipment and Test Materials

In addition to the simulator, a Maico MA-20 audiometer was used to perform hearing tests and a Titmus model OV-7M vision tester was used to check driver visual acuity. A Macintosh SE was used to present the response-time task and a Kensington Notebook 12-key number pad collected responses from drivers for that task. A Bruel and Kjaer model 2034 dual channel signal analyzer was used to analyze sounds (recorded on a Panasonic RQ332S audio tape recorder).

Instructions to subjects, biographical forms, and consent forms are contained in the appendices.

Test Sequence and Activities

Upon arrival, the subject was greeted and given a summary of the experiment. He or she signed a consent form and completed the top three sections of the biographical form. Subjects were forewarned of the possibility of motion sickness and told they could terminate the experiment at any time but still would be paid in full.

Subsequently, the subject's hearing threshold in his or her best ear was determined using an audiometer. Where subjects were unsure which ear was best, the right ear was used as it was more central to the vehicle interior. For each frequency checked, a test tone was presented at approximately 60 db to familiarize the subject with the task. Then, beginning at 30 db the tone was presented twice in 5 db decreasing steps, until it was no longer heard. Then, starting from 0 db, the intensity was increased in 5 db steps until a tone was heard. This sequence was repeated for all frequencies, one at a time, starting with the lowest frequency first.

After checking the subject's near visual acuity using the Titmus model OV-7M vision device, the response-time task was described. Subjects were then given practice trials. On each trial one of three words (brake, oil, temp) for potential warning lights appeared in 24-point font on a 9-inch monochrome CRT located in the middle of the center console. Subjects were instructed to press one of three labeled keys on the number pad (placed on the center armrest) as rapidly and accurately as possible. Response times were measured to the nearest 1/60 of a second. Due to a programming error, the number of trials in each block was not equal for all subjects. However, after this error was corrected, there were 22 practice trials occurring once, and 32 test trials for each of the three sound conditions. Each of the three stimuli occurred almost equally often. Intertrial intervals were randomly distributed, ranging from 150-524 ms in practice blocks, and 301-2077 ms apart in test trials.

After the subject completed practice, the simulator testing ensued. As shown in Table 3 there were 15 experimental blocks forming 3 groups of 5. Each group of 5 consisted of a warm-up block followed by three test blocks involving different driving conditions, and a segment containing the stop sign signaling the end of test. There was a short break between block groups to save the data, load new roads, give participants a rest, and rate the simulator realism. When certain shrubs appeared in the road scene cueing a block transition, the experimenter said the appropriate phrase (e.g., "the response time task will now begin," "now drive as fast is safe and comfortable while performing the response time task.")

Table 3. Tasks performed in each block.

Block Group	Block	Task	Duration (minutes)
1	1	warm-up	1
1	2	drive at 45 mi/hr	4
1	3	drive at 45 mi/hr with response time task	4
1	4	drive as fast is safe & comfortable with response time task	4
1	5	finish - signified by stop sign	0
1		request subjective ratings from subject	
2	6	warm-up	1
2	7	drive at 45 mi/hr	4
2	8	drive at 45 mi/hr with response time task	4
2	9	drive as fast is safe & comfortable with response time task	4
2	10	finish - signified by stop sign	0
2		request subjective ratings from subject	
3	11	warm-up	1
3	12	drive at 45 mi/hr	4
3	13	drive at 45 mi/hr with response time task	4
3	14	drive as fast is safe & comfortable with response time task	4
3	15	finish - signified by stop sign	0
3		request subjective ratings from subject	

Each of the 5 block groups corresponds to a different subset of vehicle sounds--all, speed only (no off-road or tire squeal), no sound. As shown in Table 4, the sequence was partially counterbalanced across subjects.

Table 4. Order of blocks for each subject.

Group	Subject	Initials	Order of Sound Blocks		
			1	2	3
Female < 30	1	M.C.	all	speed	none
	4	R.B.	none	speed	all
	12	N.E.	speed	none	all
	19	P.L.	none	all	speed
Male < 30	2	D.D.	all	speed	none
	3	S.H.	none	speed	all
	10	D.S.	speed	none	all
	18	A.G.	none	all	speed
Female > 60	6	J.S.	all	speed	none
	16	H.T.	none	speed	all
	17	D.J.	speed	none	all
	20	N.S.	none	all	speed
Male > 60	7	J.H.	all	speed	none
	8	J.L.	none	speed	all
	9	P.O.	speed	none	all
	13	P.D.	none	all	speed

Note: "All" sounds included the engine, wind, road/tire, shoulder sound, and tire squeal, "Speed" sounds removed shoulder noise and tire squeal, "none" was no sounds whatsoever.

Test Participants

Twenty people, all licensed drivers in the state of Michigan, were tested in this experiment. Each subject was paid $15 for participating in this experiment (which lasted between 1 and 1.5 hours). Subjects were recruited from lists maintained by the Human Factors Division. Of these 20, only 16 completed the experiment. The four who elected not to complete the experiment experienced uncomfortable "motion sickness." Of the 16 remaining, there were 8 subjects over age 60 and 8 under 30. Within each age group there were an equal number of men and women.

Subjects reported they drove from 2,000 to 31,000 miles per year (mean 13,700). All but two subjects were in the 10,000 to 25,000 mile range.

The visual acuity of the subjects ranged from 20/13 to 20/50 in the condition which they drove. All but two had 20/30 acuity or better. The measured visual acuity for each subject is given in Table 5.

Table 5. Corrected visual acuity for subjects completing the experiment.

	1	2	3	4	Mean
Female < 30	40	13	15	*25*	23
Male < 30	*18*	20	15	17	18
Female > 60	20	*25*	*30*	*25*	25
Male > 60	50	*22*	20	*25*	29

Note: Seven of the subjects (shown in italics in the table) who completed this experiment wore corrective lenses while driving.

Hearing data for these 16 subjects are shown in Table 6. As was noted earlier, most simulator sounds were below 2000 Hz. For most subjects, hearing losses below 2000 Hz were generally small, and even in the subjects with the worst hearing, the simulation generated sounds were still plainly apparent. As expected, the larger losses were found in the older drivers.

Table 6. Hearing data for subjects completing the experiment.

	250	500	1000	2000	4000	6000	8000
Mean Rising	16	13	14	14	23	28	38
Worst Rising	40	35	40	45	70	90	110
Mean Falling	14	11	10	14	23	27	36
Worst Rising	35	30	35	50	70	85	110

RESULTS

Three types of data were collected--driver performance data from the simulator, response times and errors from the in-vehicle task, and subjective ratings of simulator realism. Each was initially analyzed separately.

Data Reduction - Driving Performance Measures

As was noted earlier, the UMTRI simulator records nine variables (e.g., throttle position, steering angle, lateral position) each time the screen updates (typically at 20 Hz). For a typical 13-minute block group, there were approximately 15,600 data points. For 16 subjects, each completing 3 blocks, there are in excess of 750,000 data points, each containing nine simulator-generated variables. There was a far smaller number of data points associated with the response time and subject data.

To reduce the number of data points to be examined to a reasonable working number, custom software was written to compute mean and standard deviations for each of the 9 variables, for each 30-ft road segment, each road (a group of segments), and each test block.

Driving Performance Results

It is very difficult to select a single measure that reflects all aspects of driving performance (Green, 1993a, b). Measures considered in this report include the mean lateral position, the standard deviation of lateral position, and the mean and standard deviation of speed. If sound is helpful, people should drive closer to the center of the lane, closer to the posted speed, and more steadily (so standard deviations of the variables of interest should be reduced). As noted in the introduction, the primary effect should be on speed maintenance. Because these measures vary in their sensitivity, it is quite possible that significant changes can occur for only some of the calculated values.

To examine for significant effects ANOVA was used with the main effects being driver sex and age; subjects nested within age and sex; block group number; task combination (drive at 45 mi/hr, drive at 45 mi/hr and perform the response time task, drive at a safe and comfortable speed while performing the response time task); and sound condition (no vehicle sounds, all sounds, all sounds except tire squeal and shoulder sounds). Also included were the interactions of sound with block group and sound with the task combination. Other interactions were excluded because they were not of interest and preliminary analyses had shown them not to be statistically significant.

For the analysis of mean speed, the effects of age ($p<0.01$), subject ($p<0.01$), block group ($p<0.01$), and task combination ($p<0.001$) were all statistically significant. In general, men drove slightly faster on average (40.9 versus 40.4 mi/hr), as did younger drivers (42.5 versus 38.7 mi/hr), but by a greater margin. In terms of practice effects, subjects drove slightly faster in block 2 and 3, than in block 1 (38.7 versus 41.6 mi/hr). This suggests that somewhat more driving practice should have been given to stabilize driving performance in this experiment.

The statistical significance of sound differences (p<0.1) is marginal. Interestingly, subjects drove slightly slower than the requested: 42.1 mi/hr when asked to drive 45 without a secondary task, 41.0 when the secondary task was present (but when asked to drive 45), and 38.7 mi/hr when free to select a speed while performing the secondary task. This suggests that the dual-task condition of driving 45 mi/hr and completing the response time task was too difficult for participants, on average.

Figure 9 shows the relationship between task, the sounds presented, and mean speed. The effects of sound on mean speed do not make sense. It was expected that performance with the all sounds and speed-only sounds would be similar, since the off-road and tire-squeal sounds rarely occurred. The differences due to sound may reflect random variation.

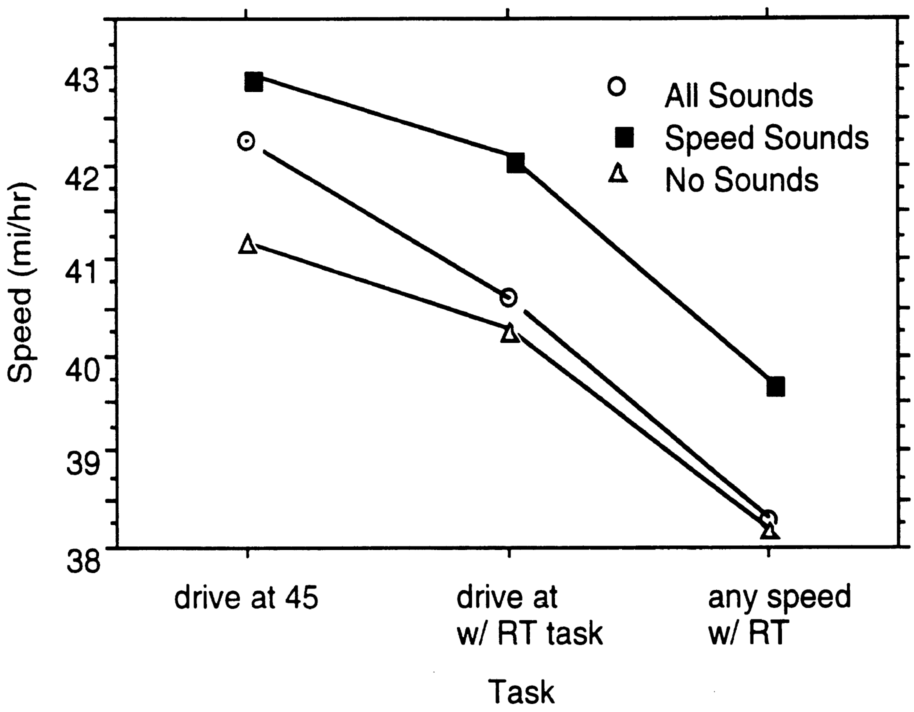


Figure 9. Mean speed as a function of task and sound treatment.

In terms of the test condition, subjects drove slower when trying to maintain 45 mi/hr and perform the response time task, than when just trying to drive at 45 mi/hr (42.1 versus 41.0 mi/hr). When allowed to select a speed, they slowed down (38.7 mi/hr). In the case of older drivers, this was done, presumably, to minimize opportunities for motion sickness. Also, as shown in Figures 10, 11, and 12, adding a secondary task added to speed variability.

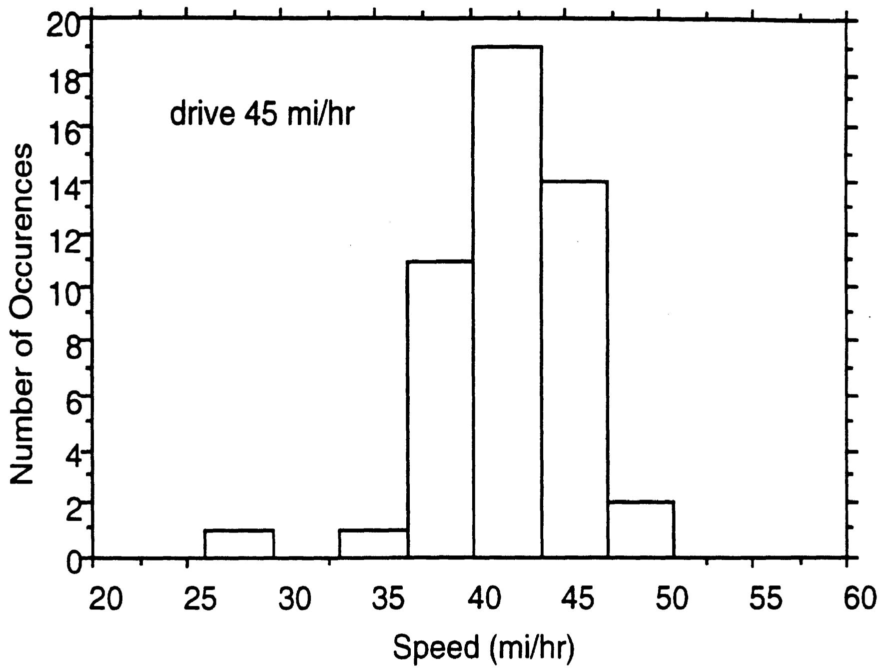


Figure 10. Distributions of speeds without a secondary task.

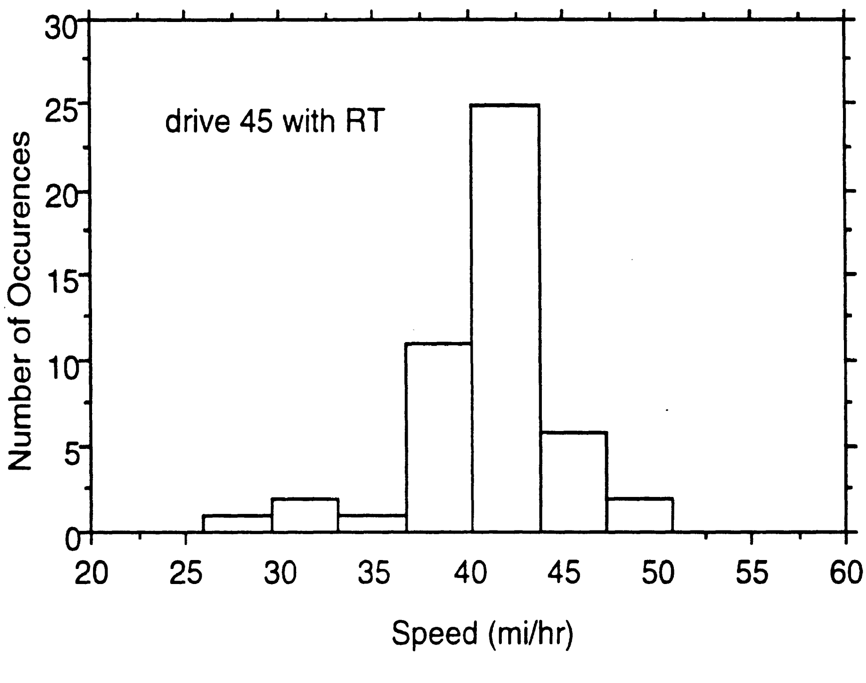


Figure 11. Distributions of speeds when instructed to drive at 45 mi/hr and perform a secondary task.

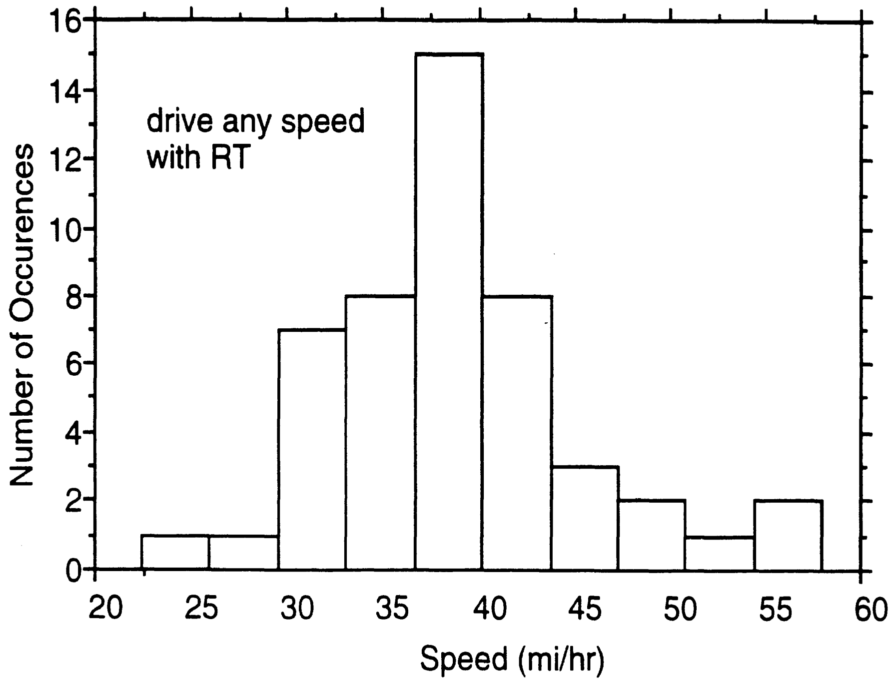


Figure 12. Distributions of speeds while performing a secondary task and free to select a speed.

The mean standard deviation of speed was 0.062 mi/hr for all participants. Older drivers were significantly less variable (0.060 versus 0.065, $p<0.05$), and the standard deviation decreased significantly ($p<0.01$) with successive trial blocks, especially between block 1 and 2 (0.077, 0.059, 0.052). There were also significant differences between subjects ($p<0.001$). Figure 13 shows the distribution of the standard deviations for all blocks.

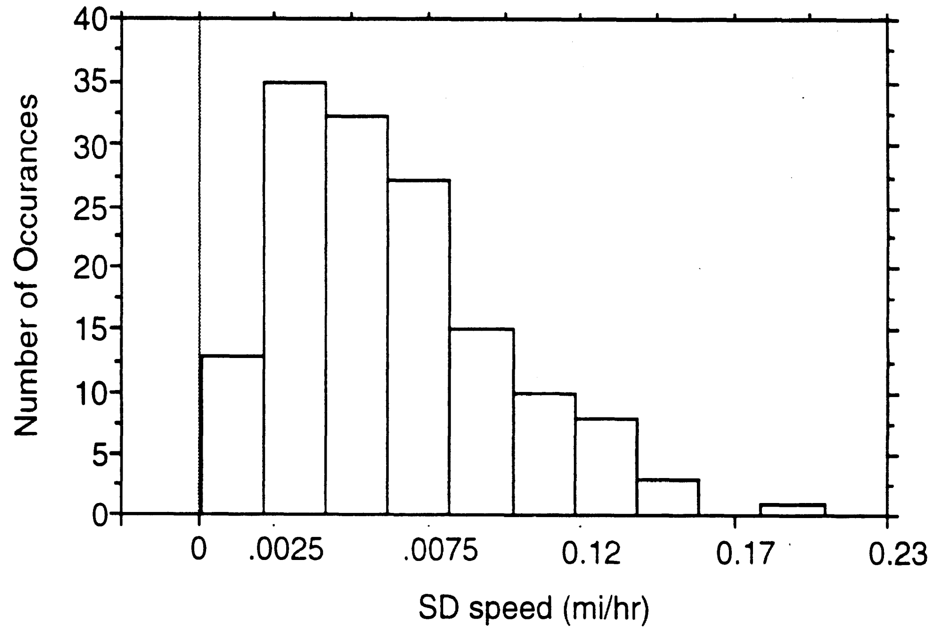


Figure 13. Distribution of the standard deviations of speed for all trial blocks.

Figure 14 shows the effects of task and sound. While the results were in the expected direction (speed was more variable in the dual task conditions), the differences were not statistically significant. Readers should bear in mind that speed maintenance was quite easy as there was no headwind and the roads were flat. Some subjects were able to drive at a constant speed by holding their right foot in a fixed position.

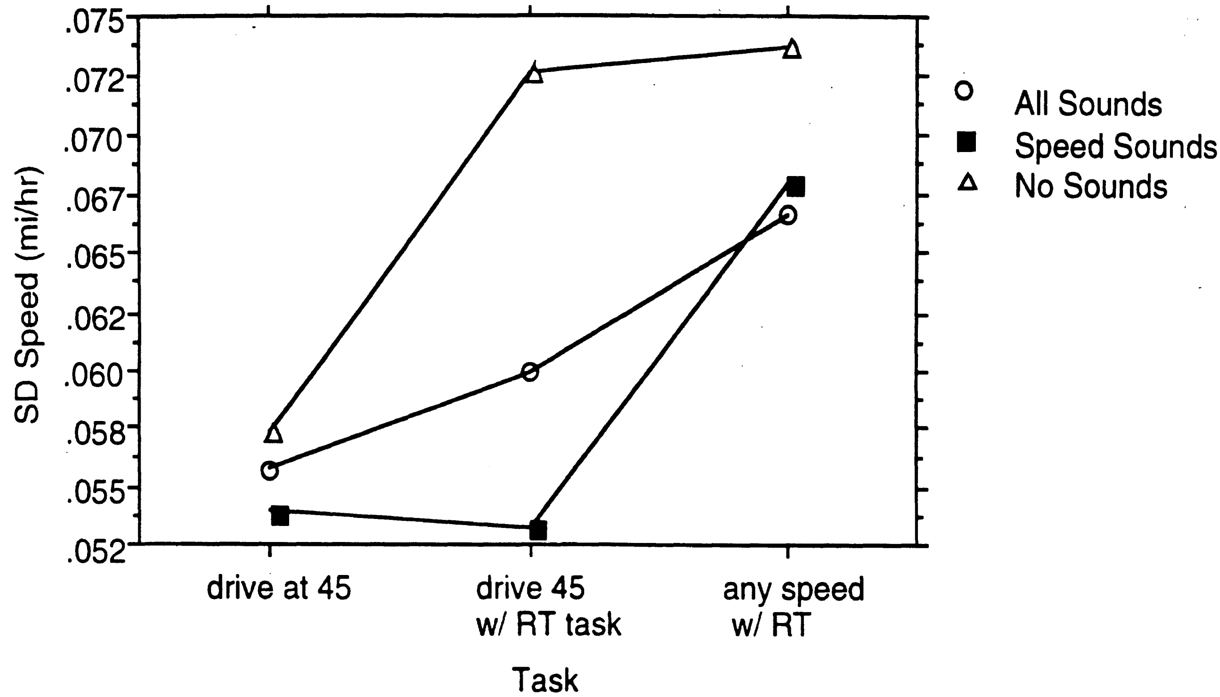


Figure 14. Effects of sound and task on the standard deviation of speed.

The mean lateral position was 3.8 ft to the right of the road centerline. Figure 15 shows the distribution. ANOVA revealed sex and age were significant (both $p<0.0001$). Women drove farther to the right (4.2 versus 3.5 ft), as did older drivers (4.0 versus 3.6 ft)

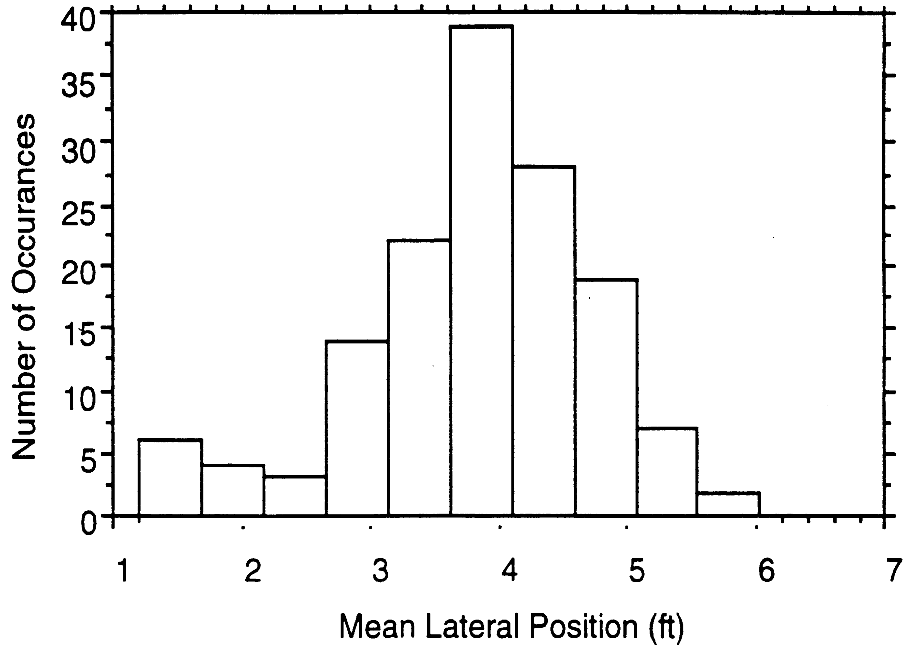


Figure 15. Distribution of the mean lateral position for all trial blocks.

Figure 16 shows the effects of sound and concurrent task upon mean lateral lane position. The differences follow no particularly explainable pattern and were not statistically significant. However, when shoulder sound was present (all-sounds condition) the position was more towards the center of the lane than in either of the other two conditions.

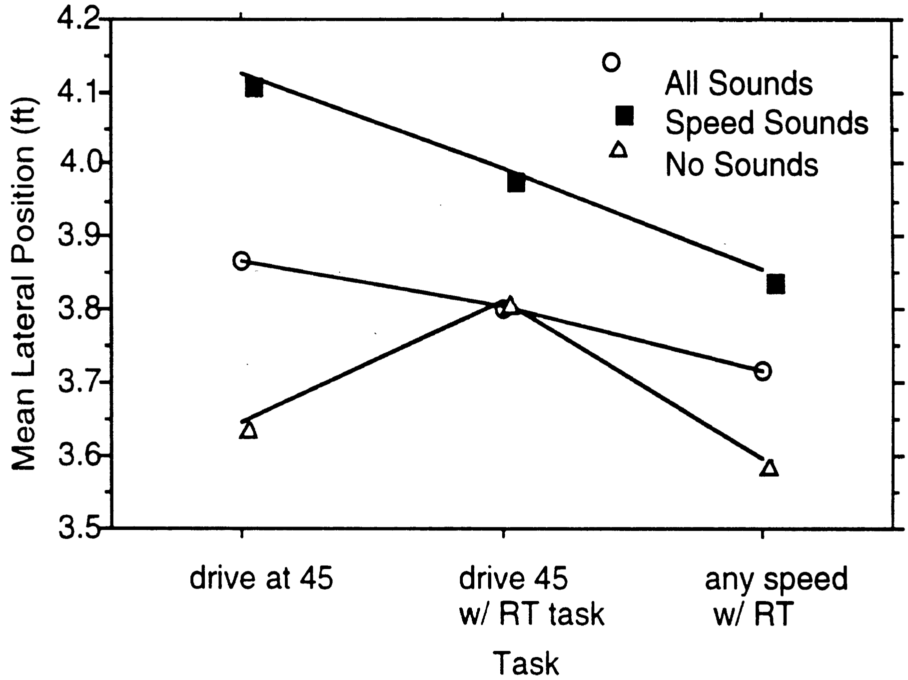


Figure 16. Effect of sound and concurrent task on the mean lateral position.

Figure 17 shows the distribution of the standard deviation of lateral position. The mean was 0.043 ft. Except for a few instances, the standard deviation was 0.05 ft or less. Significant differences in the standard deviation of lateral position were due to sex ($p<0.01$), and subject ($p<0.0001$). The standard deviation was slightly less for men than women.

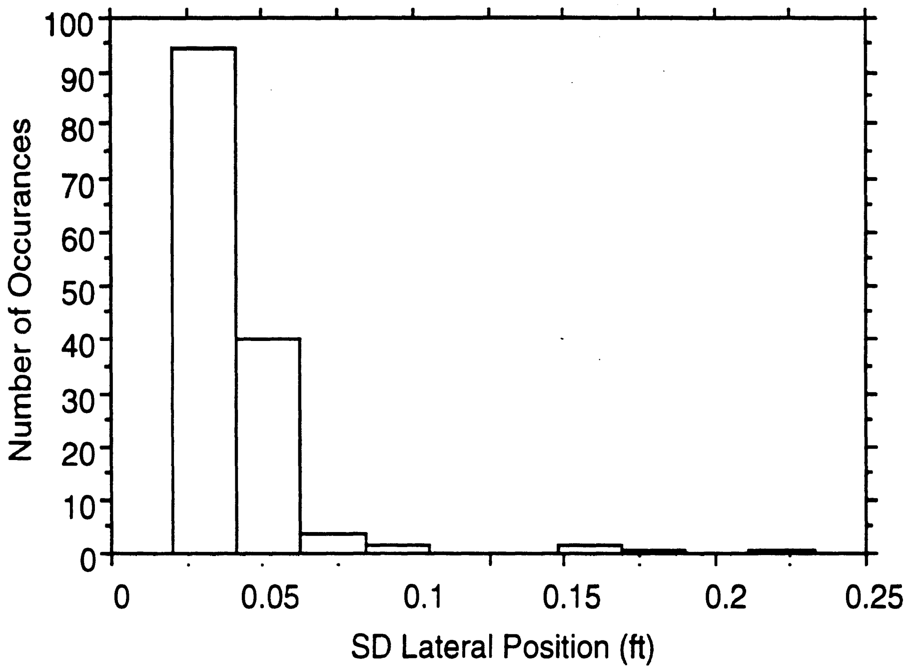


Figure 17. Distribution of the standard deviation of lateral position for all trial blocks.

Figure 18 shows the effects of sound and task combination on the standard deviation of lateral position. None of these effects was significant, though the standard deviation of lateral position was larger for conditions in which a secondary task was present than when it was not. One possibility for the poorest performance in the all-sounds condition is that tire-squeal and the shoulder sounds either distracted drivers or they misunderstood the sounds (so they behaved inappropriately).

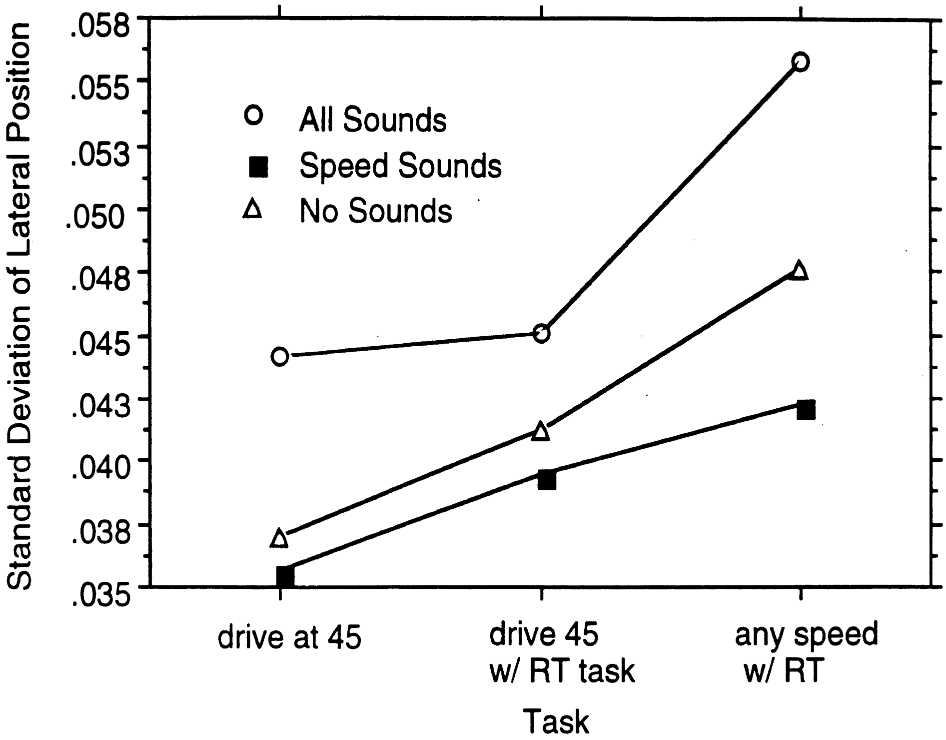


Figure 18. Effect of sound and concurrent task on the standard deviation of lateral position.

Response Time Task Results

Excluding practice trials, the mean response time was 1610 ms with an average error rate of 4.9%. The mean times for each block were analyzed using ANOVA with the main effects being sex, age group, subject nested within age and sex, block, and sound condition. None of the factors approached statistical significance (all $p>0.4$) except for subject differences, which were marginally significant ($p=0.01$). Figure 19 shows the mean response times as a function of subject sex and age. Notice that the times for older subjects are shorter, the opposite of the typical case. If fact, the subject with the largest response time was a young male (mean=2776 ms), a time almost 800 ms larger than any other subject in the sample. The shortest response time was from an older female (mean=977 ms).

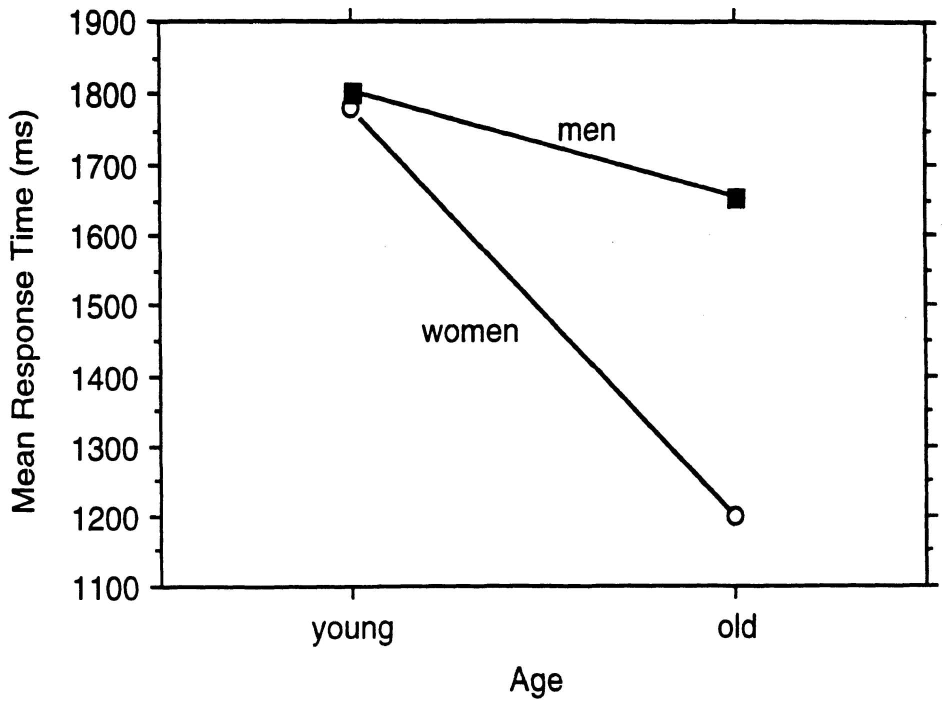


Figure 19. Mean response times as a function of driver age and gender.

The mean times were 1638 ms when all sounds were present, 1616 ms when only speed sounds were provided, and 1577 ms when no sounds were provided. Thus, providing sound did not lessen driving workload (as would be reflected in enhanced secondary task performance).

Subjective Results

Between blocks, all of the subjects rated their perceptions of the simulated driving scenario they had just experienced. The mean rating was 2.6 (where 1 = not realistic, 5 = just like a car). There were differences in rating between subjects, with men rating the simulator as slightly more realistic than women (2.7 versus 2.5). There were no differences in ratings of realism (overall) between the three sound conditions (all = 2.6, speed only = 2.7, none = 2.6) Table 7 shows the results. The slightly greater value for speed only may represent random variation or may be that the shoulder sound was not apparent to subjects (and detracted from the simulation).

Table 7. Ratings of simulator realism.

		Drive A		Drive B		Drive C
Group	Subject	Sim	Sounds	Sim	Sounds	Sim
Female < 30	1	2	3	2	3	2
	4	3	4	3.8	4	3
	12	1	3	1	4	1
	19	2.5	2.5	2.5	1	2.5
	Mean	2.13	3.13	2.33	3.00	2.13
Male < 30	2	4	4	4	4	4
	3	3	4	3	4	3
	10	2	3	2	3	2
	18	3.8	4	3.8	4	3.5
	Mean	3.20	3.75	3.20	3.75	3.13
Female > 60	6	3	4	3	4	3
	16	4	2	3	2	3
	17	3	3	3	4	3
	20	2	3	2	3	2
	Mean	3.00	3.00	2.75	3.25	2.75
Male > 60	7	1	1	1	1	1
	8	2	2	2	2	2
	9	2	2	2	2	2
	13	4	5	4.8	5	4
	Mean	2.25	2.50	2.45	2.50	2.25
	Mean	2.64	3.09	2.68	3.13	2.56

In terms of the rating of the realism of the sounds, the mean was 3.1, slightly greater than the overall rating of the simulator (again 1 = not realistic, 5 = just like a car). While individual differences were present (age, sex, subject within sex), there were no differences between conditions.

CONCLUSIONS

1. Does the presence or absence of sound affect driving performance?

Since sound provides vehicle speed cues, providing sound should enhance speed regulation. Benefits in lane position maintenance may accrue as a consequence of reducing the attentional demand required to maintain speed. Some of those benefits were evident here. Providing some kind of sound caused subjects to decrease their mean speed by 1 to 2 mi/hr and to reduce the variability in their speed, though these differences were only marginally significant in statistical tests. Providing sound had no significant effect on either mean lateral position or the standard deviation of lateral position, though subjects tended to drive closer to the center of the lane when sound was provided. These results are consistent with those of McLane and Wierwille (1975) described earlier.

In this experiment, speed maintenance was very easy as there was neither headwind nor road-induced drag variations. (This is being changed in the most recent simulator upgrade.) In fact, if drivers realized external speed disturbances were not present, and they locked their right foot in a fixed position, they could very closely regulate their speed without attending to it. In subsequent research (Reed and Green, 1995), simulator speed variance was found to be less than that for driving a comparable instrumented car on a similar road.

Thus, it appears that providing sound may lead to small (and in this experiment marginally significant) enhancements in driving performance for some measures.

2. Does the presence or absence of sound affect the sense of driving realism as perceived by the driver?

There were essentially no differences in ratings of the realism of the simulation between sound conditions. Ratings were highest when tire squeal and shoulder sounds were not present. Most likely these represent random variation in the data as those sounds occurred infrequently, though it could be that these sounds were unrealistic and detracted from the simulation.

3. Do maneuver-related sounds affect driving performance?

There were several situations where driver performance was worse when all sounds were present as opposed to when only speed-related sounds were provided. The explanation for this outcome is the same as for the ratings of realism--it could be due to either random variation or unrealistic maneuver-related sounds. All driving was intended to be under normal conditions. No maneuvers should have been performed at close to the maneuver limits of the simulator. The results might have been different had the vehicle regularly been driven to its performance limits.

Thus, as a whole, these data suggest, at least for the conditions and task explored, that vehicle-related sounds have some importance for speed maintenance but are unimportant for lane keeping. While the lane-keeping data make sense, larger effects on speed maintenance were expected at the outset of this experiment. In retrospect, the results are reasonable given the very easy speed maintenance task (no wind-induced drag variations, a feature later added to the simulator). Nonetheless, the authors believe that the simulation is reasonable and suggestive of something fundamental concerning the impact of sound on driving performance. However, it does not justify developing high-quality simulations of driving sounds for studies of driving performance. Studies of customer impressions of automotive products are a different matter.

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APPENDIX A - CONSENT FORM

Simulator Sound Evaluation - Participant Consent Form

The purpose of this experiment is to determine the extent to which drivers use auditory cues while driving a vehicle.

During the experiment you will be seated in a driving simulator and a road scene will be projected onto a screen in front of you. The steering wheel, accelerator, brake and speedometer are fully functional, such that you should drive the simulated vehicle just as you would your own vehicle on public roads.

Because you are driving a simulator in the laboratory, nothing will happen if you are involved in a simulated accident. However, since we are trying to examine real driving behavior, we ask that you drive as you normally would, that is, safely.

Because our simulation is imperfect, about 1 out of 8 people experience some motion discomfort (they feel a bit queasy) while driving the simulator. This is most noticeable when you make turns or quick lane changes. If at any time you feel motion discomfort, let us know and we can stop the experiment. Please realize that your personal performance is not an issue in this experiment, the primary concern here is the realism of the simulation and the sound cues being presented.

The experiment will take between 1 and 1.5 hours, for which you will be paid $15.00. If you have any problems or discomfort while participating in this experiment, you can withdraw at any time. You will be paid regardless.

A few of the sessions will be videotaped. Do you object to being videotaped?

yes   no

I have read and understand the information above.

______________________________ Print your name

____________________ Date

______________________________ Sign your name

____________________ Witness (experimenter)

APPENDIX B - BIOGRAPHICAL FORM

University of Michigan Transportation Research Institute
Human Factors Division

Simulator Sound Evaluation Biographical Form

Subject: ☐

Date: ☐

Name: ______________________________

Male Female (circle one) Age : ____________

Education:
(Circle Highest Level Completed)

some high school	high school diploma
some trade/tech school	trade/tech scool degree
some college	college degree

Occupation / Major: ______________________________

What kind of car do you drive the most?

Year: ________ Make: ________ Model: ________

Annual Mileage : ____________

Do you have any driving restrictions? YES NO

If Yes, please explain: ______________________________

How often do you experience motion sickness while driving?

very often | moderately often | neutral | seldom | never

While flying?

very often | moderately often | neutral | seldom | never

While boating?

very often | moderately often | neutral | seldom | never

TITMUS VISION: (Landolt Rings)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	corrective lenses worn?	
T	R	R	L	T	B	L	R	L	B	R	B	T	R		
20/200	20/100	20/70	20/50	20/40	20/35	20/30	20/25	20/22	20/20	20/18	20/17	20/15	20/13	yes	no

AUDIOMETRIC TEST

Frequency :	250	500	1000	2000	4000	6000	8000	Hearing assistance worn?
Rising:	___	___	___	___	___	___	___	
dB loss								
Falling:	___	___	___	___	___	___	___	yes no

APPENDIX C - SUBJECT QUESTIONNAIRE

Sound Verification Experiment Questionnaire

Subject Name : ______________________________

Subject Number : ______________________________

First Sound Set Presented : _______________

How would you rate the Realism of the Simulation :

1 2 3 4 5

Not Realistic Just like a Car

How would you rate the Realism of the Sounds Presented :

1 2 3 4 5

Not Realistic Just like a Car

Second Sound Set Presented : _______________

How would you rate the Realism of the Simulation :

1 2 3 4 5

Not Realistic Just like a Car

How would you rate the Realism of the Sounds Presented :

1 2 3 4 5

Not Realistic Just like a Car

Third Sound Set Presented : _______________

How would you rate the Realism of the Simulation :

1 2 3 4 5

Not Realistic Just like a Car

How would you rate the Realism of the Sounds Presented :

1 2 3 4 5

Not Realistic Just like a Car

APPENDIX D - ROAD DESCRIPTION

link	type	radius (ft)	pitch (rad)	length (ft)
Snd_V.warmup	straight	0	0	450
Snd_V.warmup	right curve	500	0	0
Snd_V.warmup	straight	0	3.4357	420
Snd_V.warmup	left curve	500	4.5788	0
Snd_V.warmup	straight	0	4.5788	600
Snd_V.warmup	left curve	500	2.2912	0
Snd_V.warmup	straight	0	7.9953	750
Snd_V.warmup	right curve	0	0	0
Snd_V.road1	straight	0	0	450
Snd_V.road1	right curve	500	0	0
Snd_V.road1	straight	0	1.7186	420
Snd_V.road1	left curve	500	1.7186	0
Snd_V.road1	straight	0	1.7186	600
Snd_V.road1	left curve	500	2.2912	0
Snd_V.road1	straight	0	6.8591	870
Snd_V.road1	left curve	1000	4.5788	0
Snd_V.road1	right curve	1000	4.5788	0
Snd_V.road1	straight	0	0	150
Snd_V.road1	right curve	500	2.2912	0
Snd_V.road1	straight	0	5.7201	300
Snd_V.road1	left curve	1500	4.0075	0
Snd_V.road1	right curve	2000	4.0075	0
Snd_V.road1	straight	0	0	240
Snd_V.road1	left curve	2714	1.7186	0
Snd_V.road1	straight	0	2.2912	630
Snd_V.road1	right curve	500	1.1459	0
Snd_V.road1	straight	0	1.7186	420
Snd_V.road1	left curve	500	2.8636	0
Snd_V.road1	straight	0	2.8636	600
Snd_V.road1	left curve	500	2.2912	0
Snd_V.road1	straight	0	6.8591	870
Snd_V.road1	left curve	1000	4.5788	0
Snd_V.road1	right curve	1000	4.5788	0
Snd_V.road1	straight	0	0	150
Snd_V.road1	right curve	500	2.2912	0
Snd_V.road1	straight	0	5.7201	300
Snd_V.road1	left curve	1500	3.4357	0
Snd_V.road1	straight	0	5.7201	660
Snd_V.road1	left curve	1200	6.8591	0
Snd_V.road1	straight	0	9.1284	540
Snd_V.road1	left curve	500	2.2912	0
Snd_V.road1	straight	0	6.8591	570
Snd_V.road1	left curve	1000	4.5788	0
Snd_V.road1	right curve	1000	4.5788	0
Snd_V.road1	straight	0	0	150
Snd_V.road1	right curve	500	2.2912	0
Snd_V.road1	straight	0	5.7201	300
Snd_V.road1	left curve	1500	4.0075	0
Snd_V.road1	right curve	2000	4.0075	0
Snd_V.road1	straight	0	0	240
Snd_V.road1	left curve	2714	1.7186	0
Snd_V.road1	straight	0	2.2912	630
Snd_V.road1	right curve	0	20.1400	0
Snd_V.road2	straight	0	0	450
Snd_V.road2	right curve	500	0	0
Snd_V.road2	straight	0	1.7186	420
Snd_V.road2	left curve	500	1.7186	0
Snd_V.road2	straight	0	1.7186	600

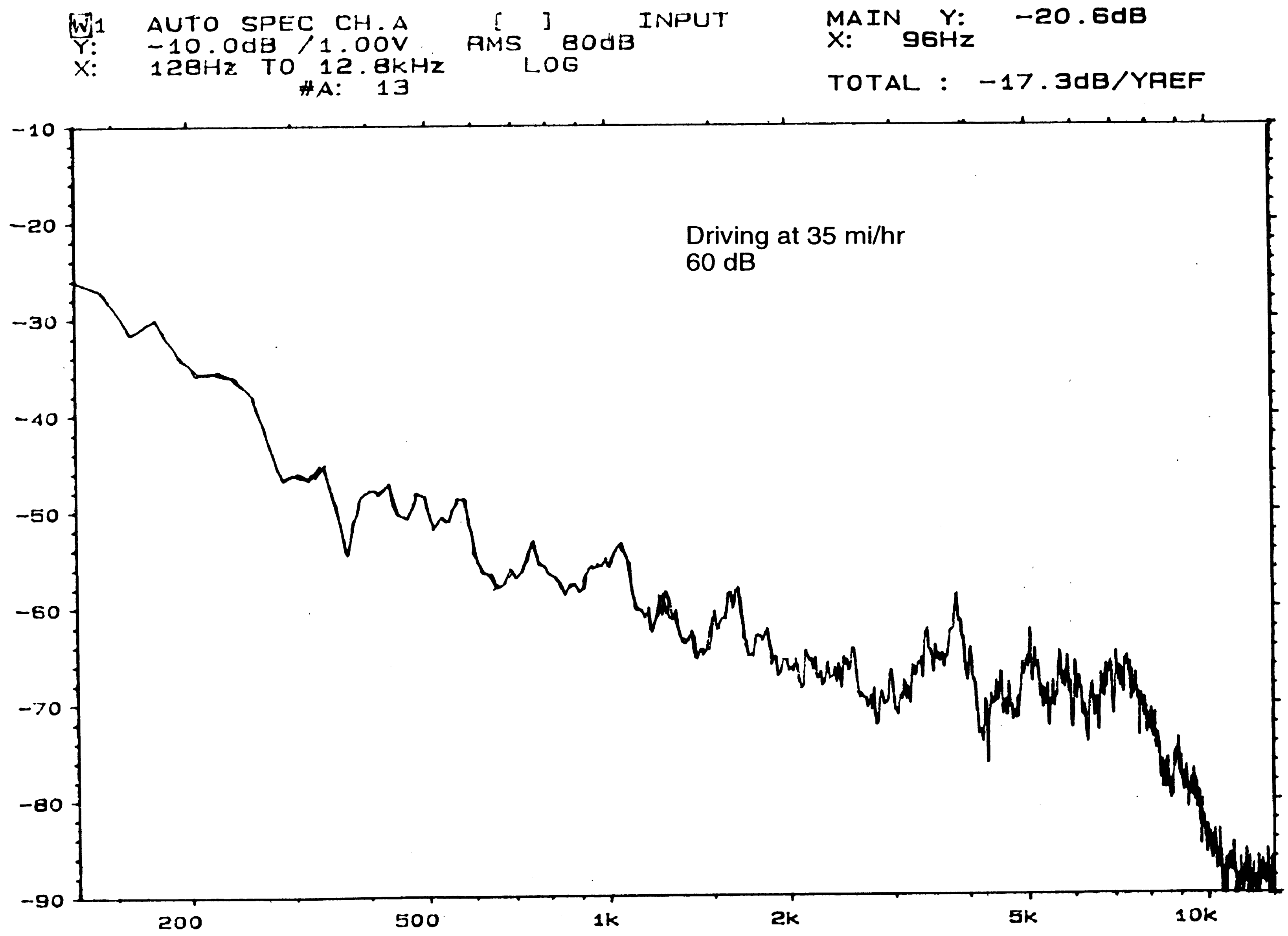
Snd_V.road2	left curve	500	2.2912	0
Snd_V.road2	straight	0	6.8591	870
Snd_V.road2	left curve	1000	4.5788	0
Snd_V.road2	right curve	1000	4.5788	0
Snd_V.road2	straight	0	0	150
Snd_V.road2	right curve	500	2.2912	0
Snd_V.road2	straight	0	5.7201	300
Snd_V.road2	left curve	1500	4.0075	0
Snd_V.road2	right curve	2000	4.0075	0
Snd_V.road2	straight	0	0	240
Snd_V.road2	left curve	2714	1.7186	0
Snd_V.road2	straight	0	2.2912	630
Snd_V.road2	right curve	500	1.1459	0
Snd_V.road2	straight	0	1.7186	420
Snd_V.road2	left curve	500	2.8636	0
Snd_V.road2	straight	0	2.8636	600
Snd_V.road2	left curve	500	2.2912	0
Snd_V.road2	straight	0	6.8591	870
Snd_V.road2	left curve	1000	4.5788	0
Snd_V.road2	right curve	1000	4.5788	0
Snd_V.road2	straight	0	0	150
Snd_V.road2	right curve	500	2.2912	0
Snd_V.road2	straight	0	5.7201	300
Snd_V.road2	left curve	1500	3.4357	0
Snd_V.road2	straight	0	5.7201	660
Snd_V.road2	left curve	1200	6.8591	0
Snd_V.road2	straight	0	9.1284	540
Snd_V.road2	left curve	500	2.2912	0
Snd_V.road2	straight	0	6.8591	570
Snd_V.road2	left curve	1000	4.5788	0
Snd_V.road2	right curve	1000	4.5788	0
Snd_V.road2	straight	0	0	150
Snd_V.road2	right curve	500	2.2912	0
Snd_V.road2	straight	0	5.7201	300
Snd_V.road2	left curve	1500	4.0075	0
Snd_V.road2	right curve	2000	4.0075	0
Snd_V.road2	straight	0	0	240
Snd_V.road2	left curve	2714	1.7186	0
Snd_V.road2	straight	0	2.2912	630
Snd_V.road2	right curve	0	20.1400	0
Snd_V.road3	straight	0	0	450
Snd_V.road3	right curve	750	0	0
Snd_V.road3	straight	0	0	180
Snd_V.road3	left curve	625	3.4357	0
Snd_V.road3	straight	0	3.4357	810
Snd_V.road3	left curve	750	1.1459	0
Snd_V.road3	right curve	612	7.9953	0
Snd_V.road3	straight	0	2.2912	210
Snd_V.road3	left curve	520	4.5788	0
Snd_V.road3	straight	0	5.7201	900
Snd_V.road3	right curve	447	7.9953	0
Snd_V.road3	straight	0	4.2932	540
Snd_V.road3	right curve	500	2.5775	0
Snd_V.road3	left curve	429	1.7186	0
Snd_V.road3	straight	0	1.7186	540
Snd_V.road3	left curve	429	1.7186	0
Snd_V.road3	straight	0	1.7186	510
Snd_V.road3	left curve	440	4.0075	0
Snd_V.road3	straight	0	4.5788	750
Snd_V.road3	right curve	500	4.0075	0
Snd_V.road3	straight	0	2.8636	150
Snd_V.road3	right curve	632	2.2912	0
Snd_V.road3	left curve	750	4.5788	0
Snd_V.road3	straight	0	6.8591	570

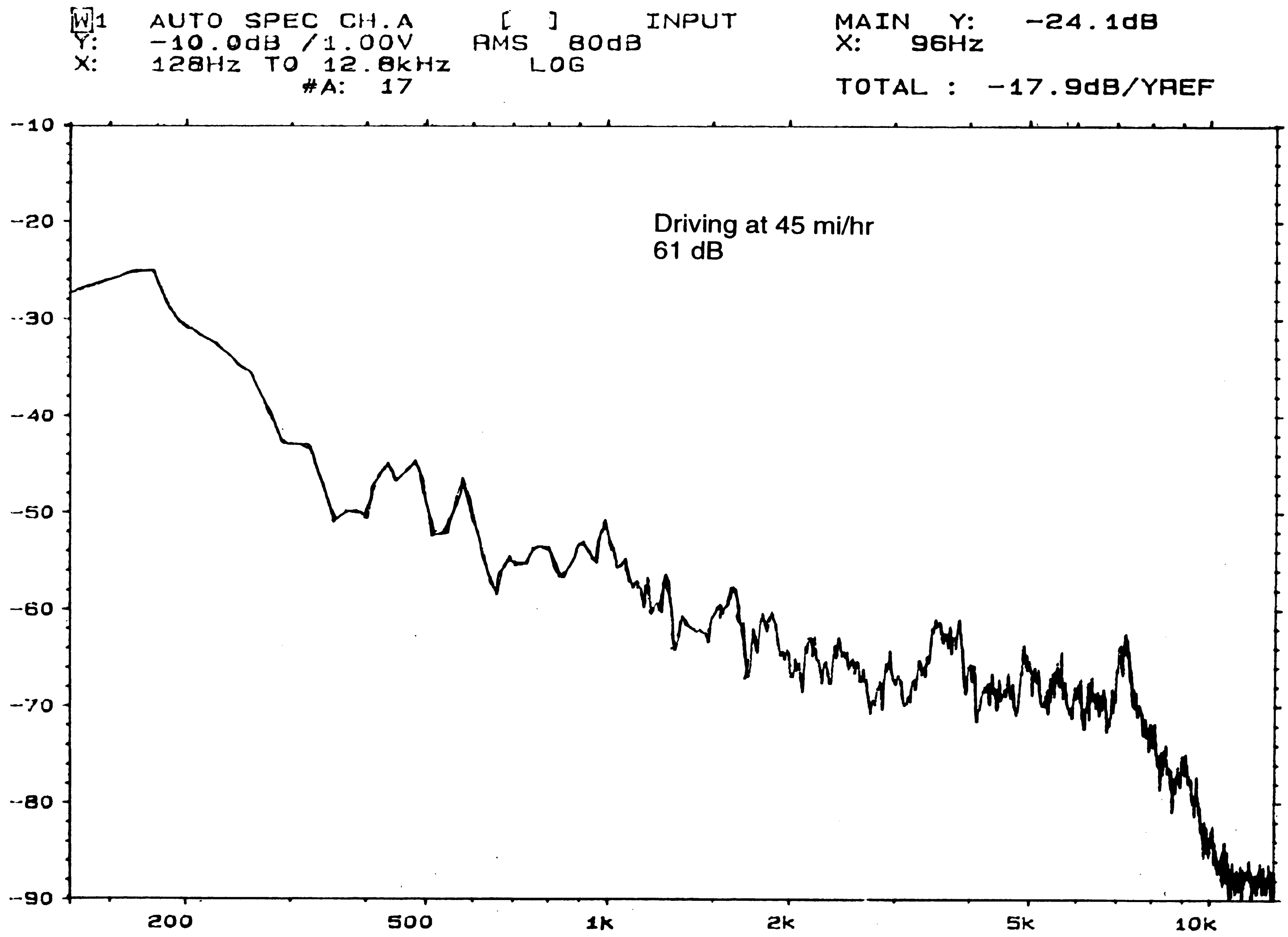
Snd_V.road3	left curve	459	1.7186	0
Snd_V.road3	straight	0	4.5788	660
Snd_V.road3	right curve	1000	6.8591	0
Snd_V.road3	straight	0	0	120
Snd_V.road3	right curve	553	13.0623	0
Snd_V.road3	straight	0	5.7201	480
Snd_V.road3	left curve	600	4.0075	0
Snd_V.road3	straight	0	6.8591	600
Snd_V.road3	left curve	500	1.7186	0
Snd_V.road3	straight	0	1.7186	420
Snd_V.road3	right curve	714	0.5730	0
Snd_V.road3	straight	0	1.7186	90
Snd_V.road3	left curve	402	6.2899	0
Snd_V.road3	straight	0	9.1284	480
Snd_V.road3	right curve	477	4.5788	0
Snd_V.road3	straight	0	0	150
Snd_V.road3	left curve	500	1.7186	0
Snd_V.road3	straight	0	3.4357	810
Snd_V.road3	right curve	474	0	0
Snd_V.road3	straight	0	0	90
Snd_V.road3	left curve	600	3.4357	0
Snd_V.road3	straight	0	7.9953	720
Snd_V.road3	right curve	405	3.4357	0
Snd_V.road3	straight	0	0	210
Snd_V.road3	left curve	457	7.4276	0
Snd_V.road3	straight	0	10.8209	600
Snd_V.road3	right curve	507	7.9953	0
Snd_V.road3	straight	0	2.2912	210
Snd_V.road3	left curve	459	4.5788	0
Snd_V.road3	straight	0	6.2899	540
Snd_V.road3	right curve	482	0	0
Snd_V.road3	left curve	533	1.7186	0
Snd_V.road3	straight	0	3.4357	810
Snd_V.road3	right curve	333	0	0
Snd_V.road3	straight	0	1.1459	90
Snd_V.road3	left curve	435	6.8591	0
Snd_V.road3	straight	0	10.8209	840
Snd_V.road3	right curve	402	4.0075	0
Snd_V.road3	straight	0	0	360
Snd_V.road3	left curve	429	6.8591	0
Snd_V.road3	straight	0	11.3830	600
Snd_V.road3	left curve	500	2.2912	0
Snd_V.road3	straight	0	4.5788	720
Snd_V.road3	right curve	333	0	0
Snd_V.road3	straight	0	1.7186	120
Snd_V.road3	left curve	500	0	0
Snd_V.road3	straight	0	1.7186	600
Snd_V.road3	left curve	750	0	0
Snd_V.road3	straight	0	0	510
Snd_V.road3	right curve	450	4 5788	0
Snd_V.end	straight	0	0	900

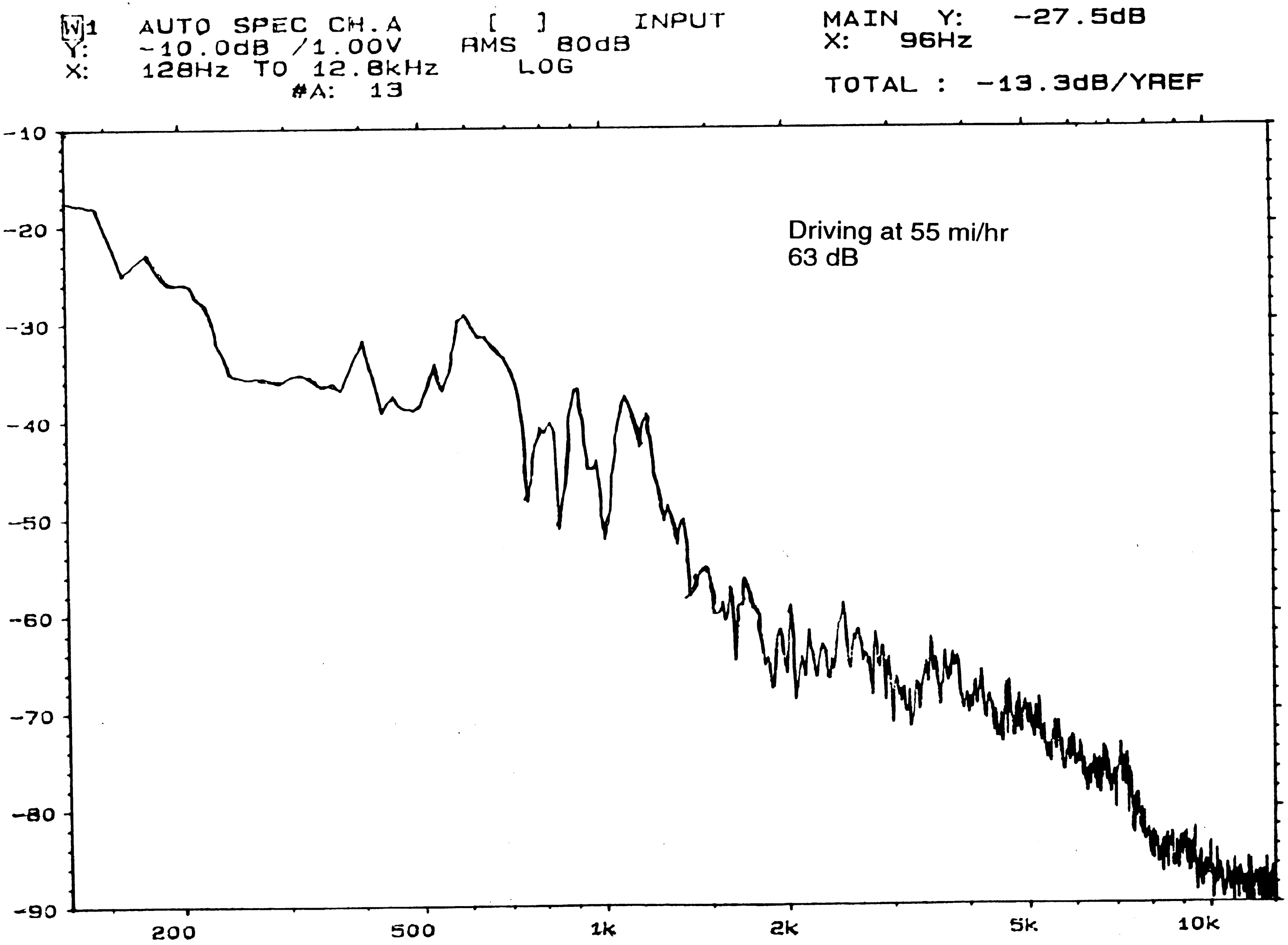
APPENDIX E - SOUND SAMPLES

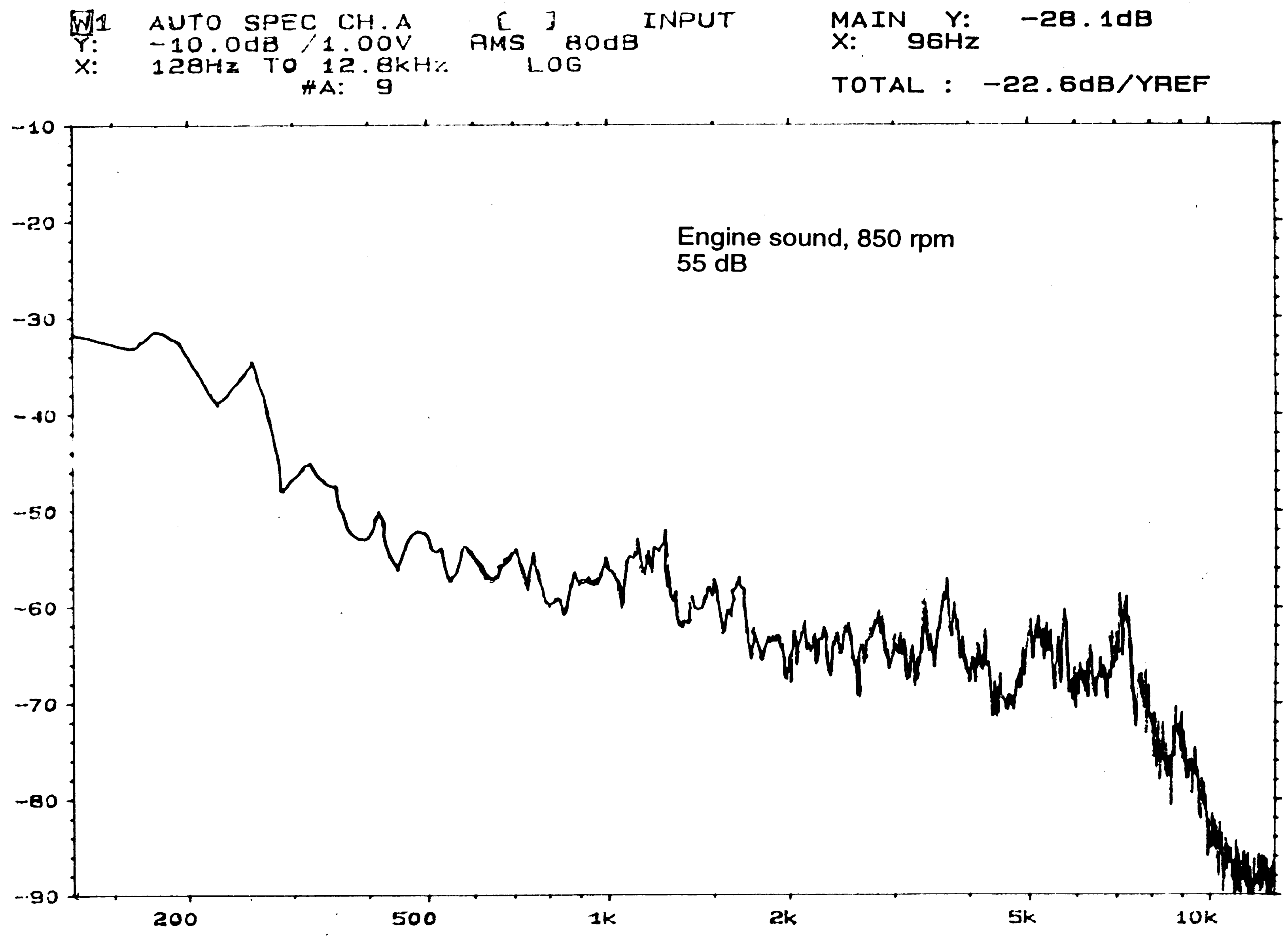
Overall levels measured during playback through a signal analyzer.

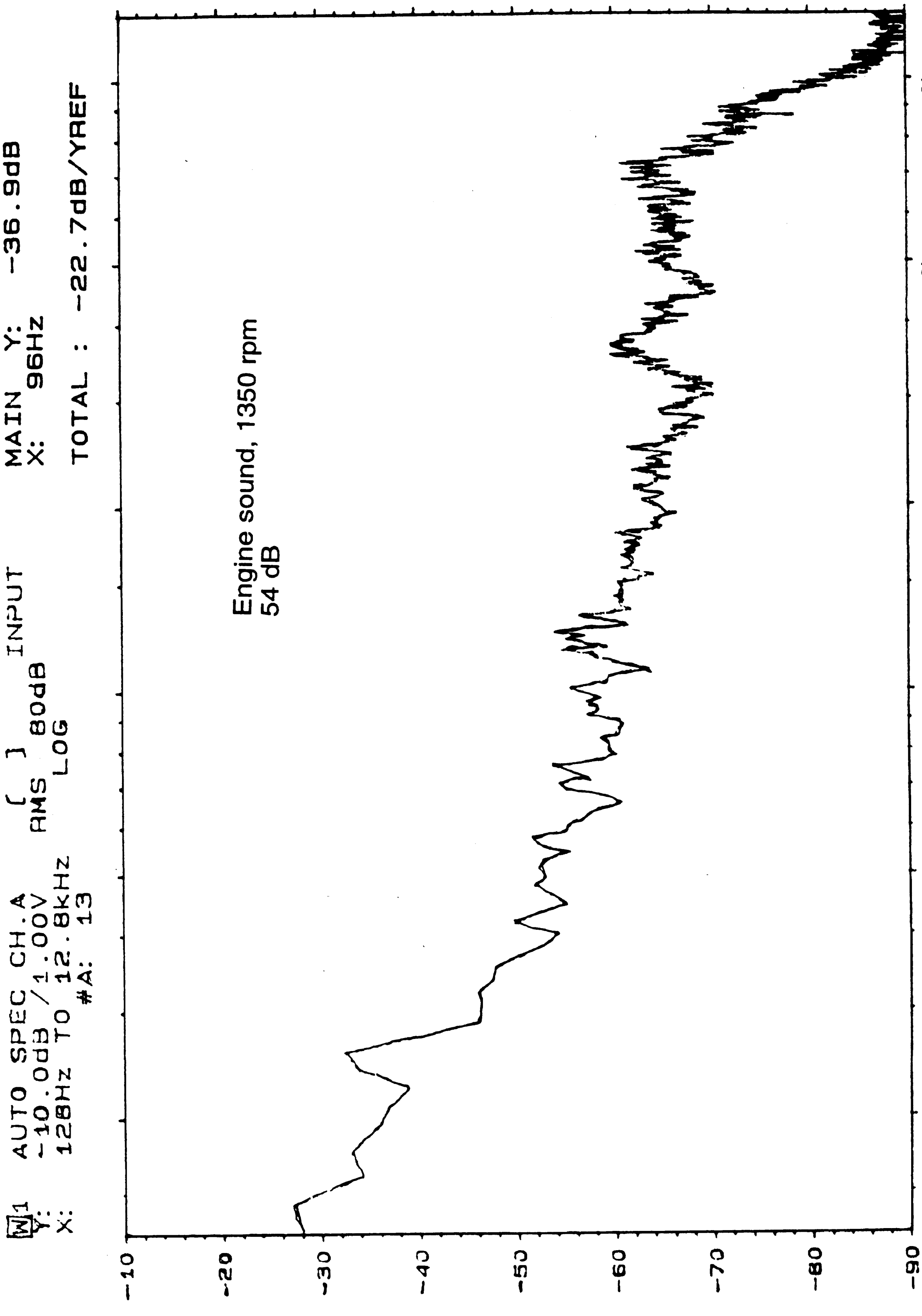
Sample	Intensity at Playback (db)
850 rpm	55.
1350 rpm	54.
2030 rpm	56.
2700 rpm	63.
3470 rpm	61.
4230 rpm	66.
4920 rpm	69.
5710 rpm	65.
road/tire sound	62.
shoulder sound	58.
tire squeal	68.
wind	64.

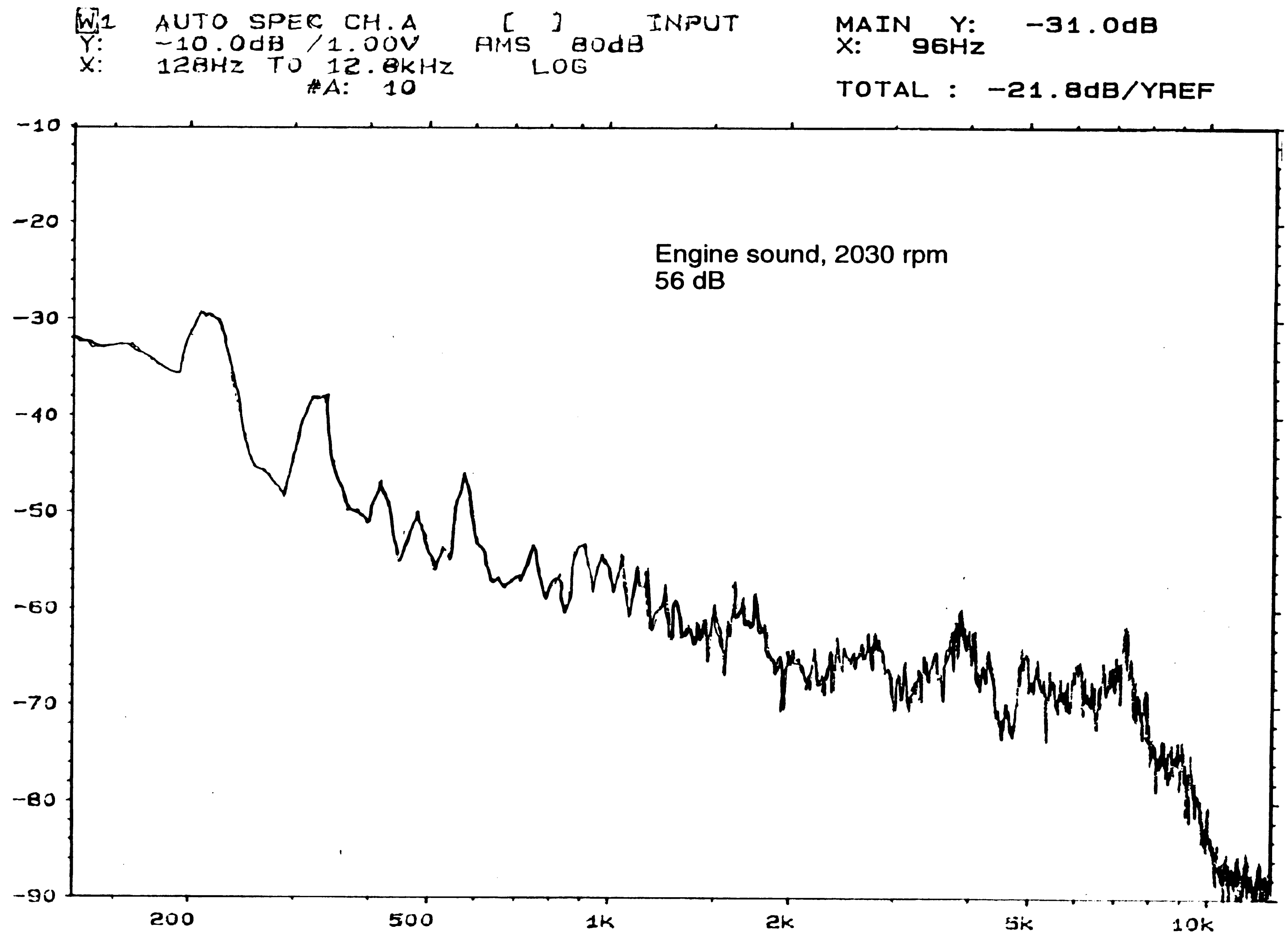

W1 AUTO SPEC CH.A [ ] INPUT
Y: -10.0dB /1.00V RMS 80dB
X: 128Hz TO 12.8kHz LOG
#A: 13
MAIN Y: -20.6dB
X: 96Hz
TOTAL : -17.3dB/YREF
Driving at 35 mi/hr
60 dB
-10
-20
-30
-40
-50
-60
-70
-80
-90
200
500
1k
2k
5k
10k


W1 AUTO SPEC CH.A [ ] INPUT
Y: -10.0dB /1.00V RMS 80dB
X: 128Hz TO 12.8kHz LOG
#A: 17
MAIN Y: -24.1dB
X: 96Hz
TOTAL : -17.9dB/YREF
Driving at 45 mi/hr
61 dB
-10
-20
-30
-40
-50
-60
-70
-80
-90
200
500
1k
2k
5k
10k

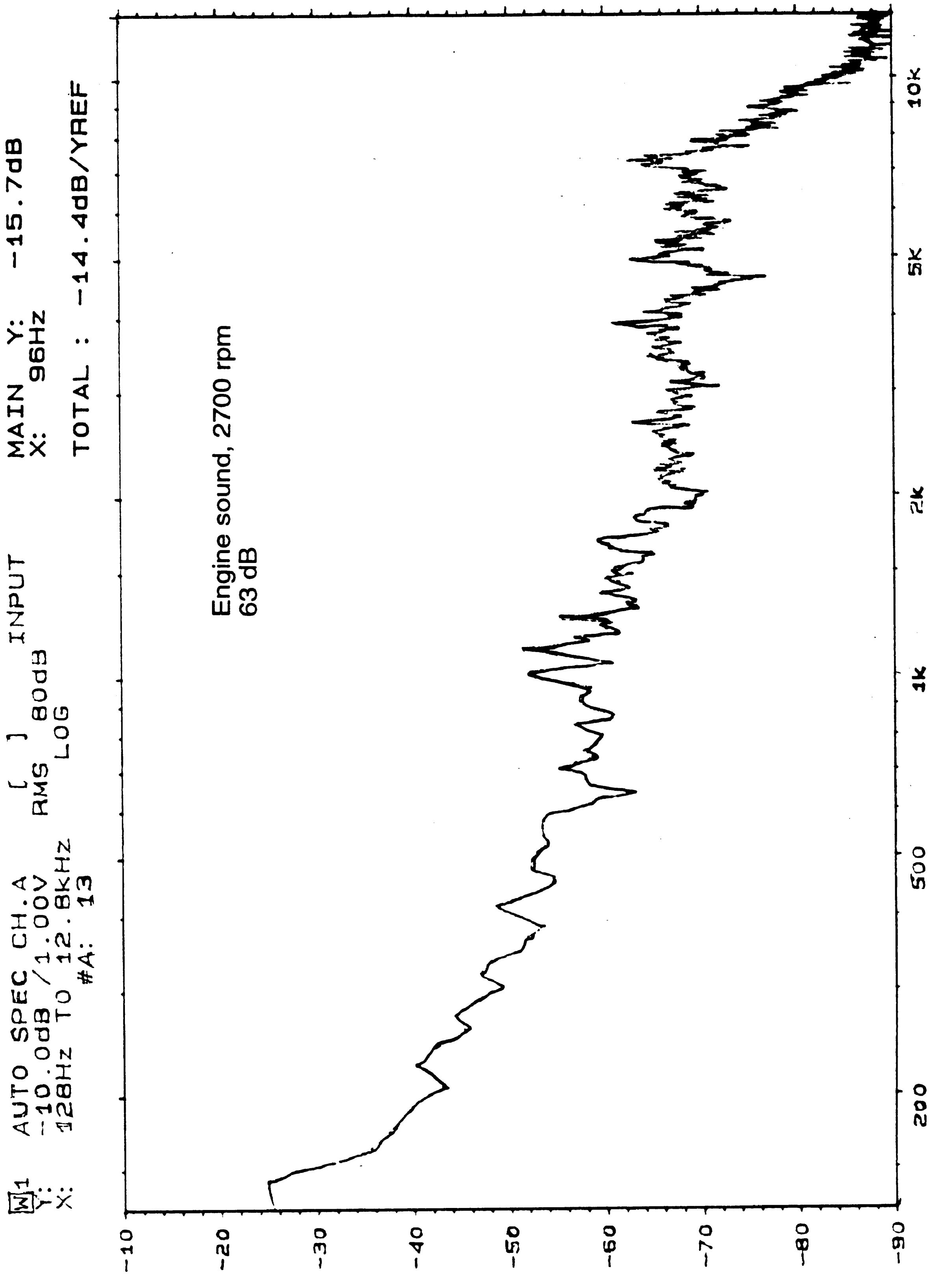

W1 AUTO SPEC CH.A [ ] INPUT
Y: -10.0dB /1.00V RMS 80dB
X: 128Hz TO 12.8kHz LOG
#A: 13
MAIN Y: -27.5dB
X: 96Hz
TOTAL : -13.3dB/YREF
Driving at 55 mi/hr
63 dB
-10
-20
-30
-40
-50
-60
-70
-80
-90
200
500
1k
2k
5k
10k

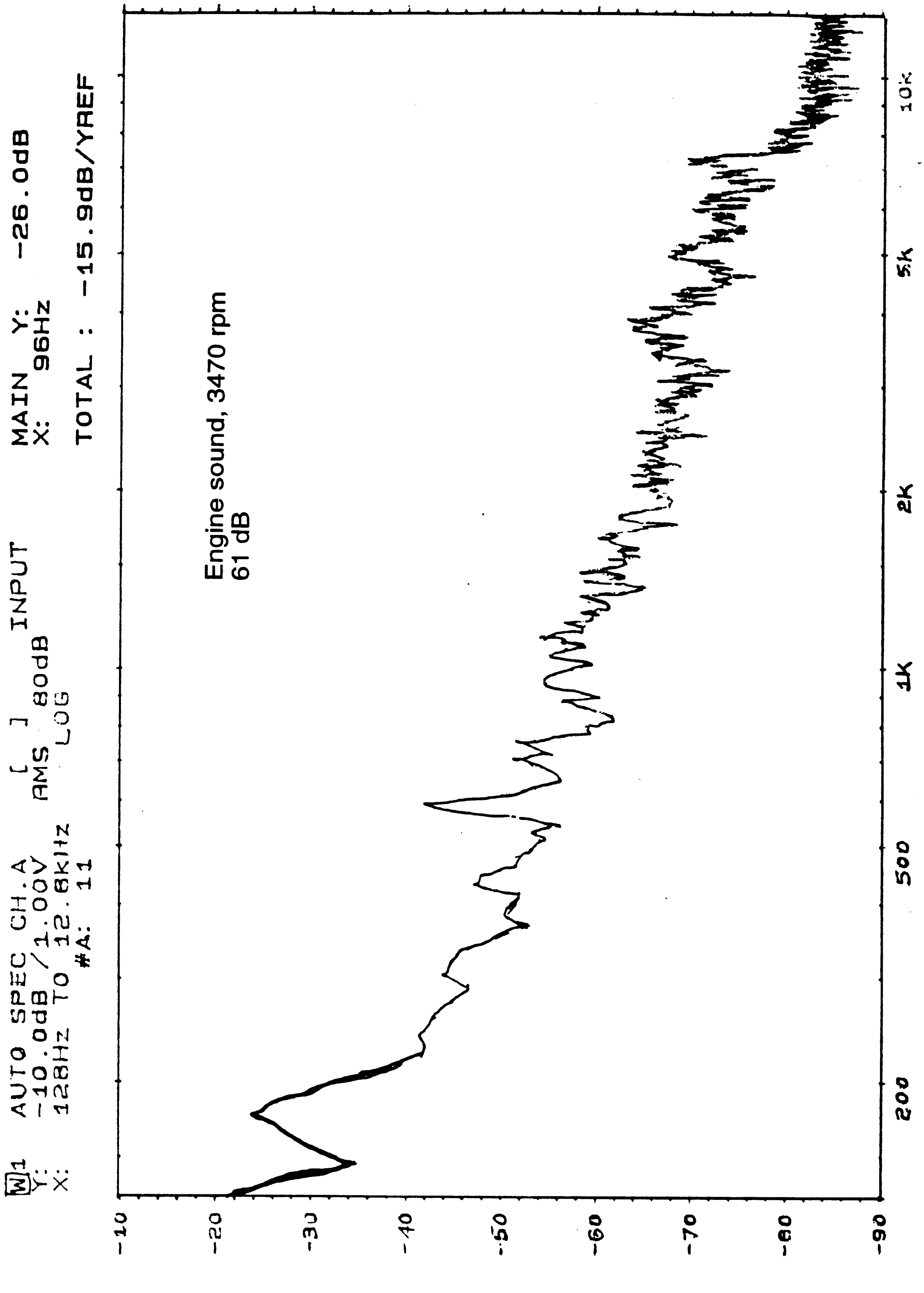

W1 AUTO SPEC CH.A [ ] INPUT
Y: -10.0dB /1.00V RMS 80dB
X: 128Hz TO 12.8kHz LOG
#A: 9
MAIN Y: -28.1dB
X: 96Hz
TOTAL : -22.6dB/YREF
Engine sound, 850 rpm
55 dB
-10
-20
-30
-40
-50
-60
-70
-80
-90
200
500
1k
2k
5k
10k

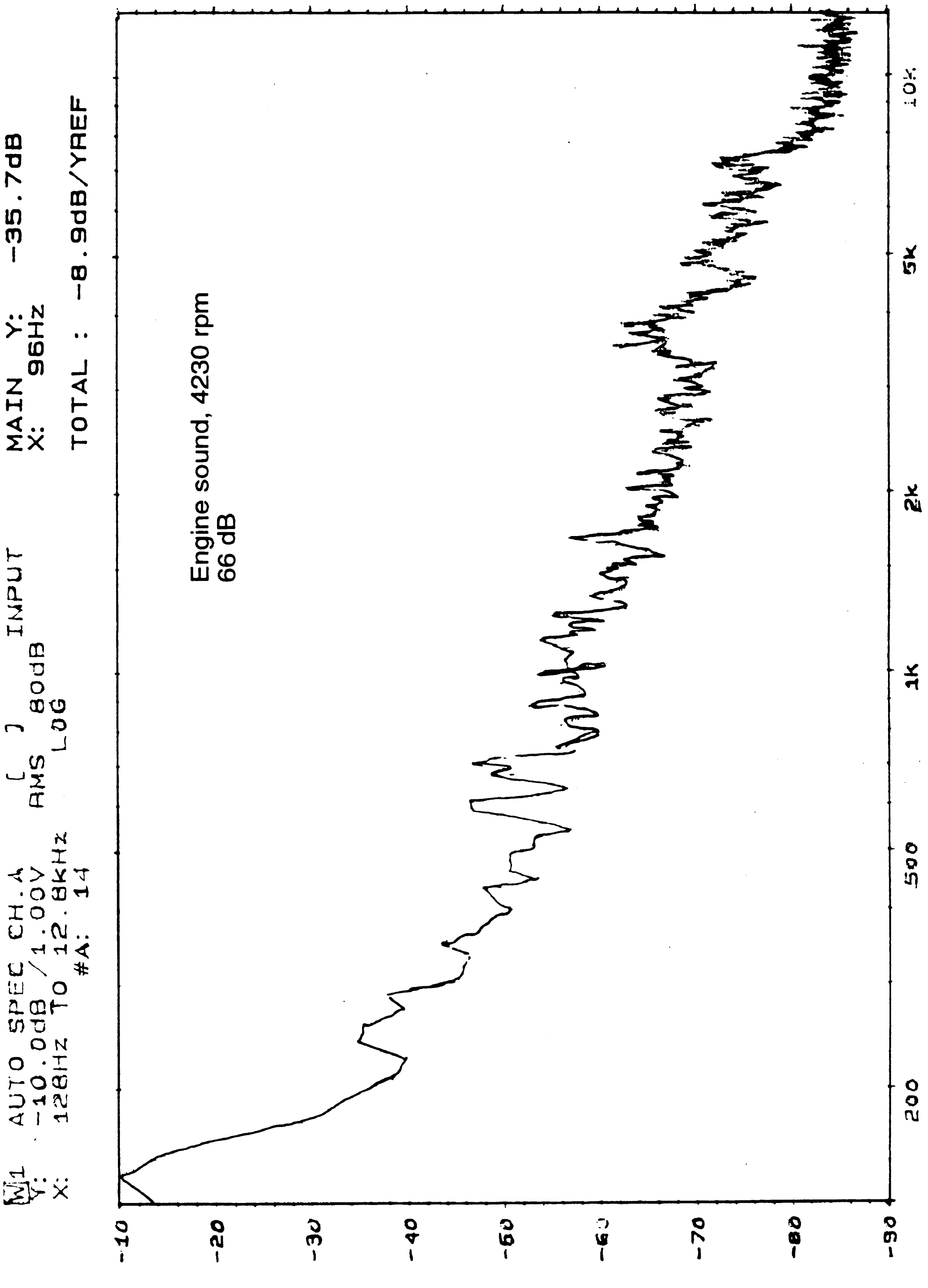

W1
Y: AUTO SPEC CH.A [ ] INPUT
-10.0dB / 1.00V RMS 80dB
X: 128Hz TO 12.8kHz LOG
#A: 13
MAIN Y: -36.9dB
X: 96Hz
TOTAL : -22.7dB/YREF
Engine sound, 1350 rpm
54 dB
-10
-20
-30
-40
-50
-60
-70
-80
-90
200
500
1k
2k
5k
10k

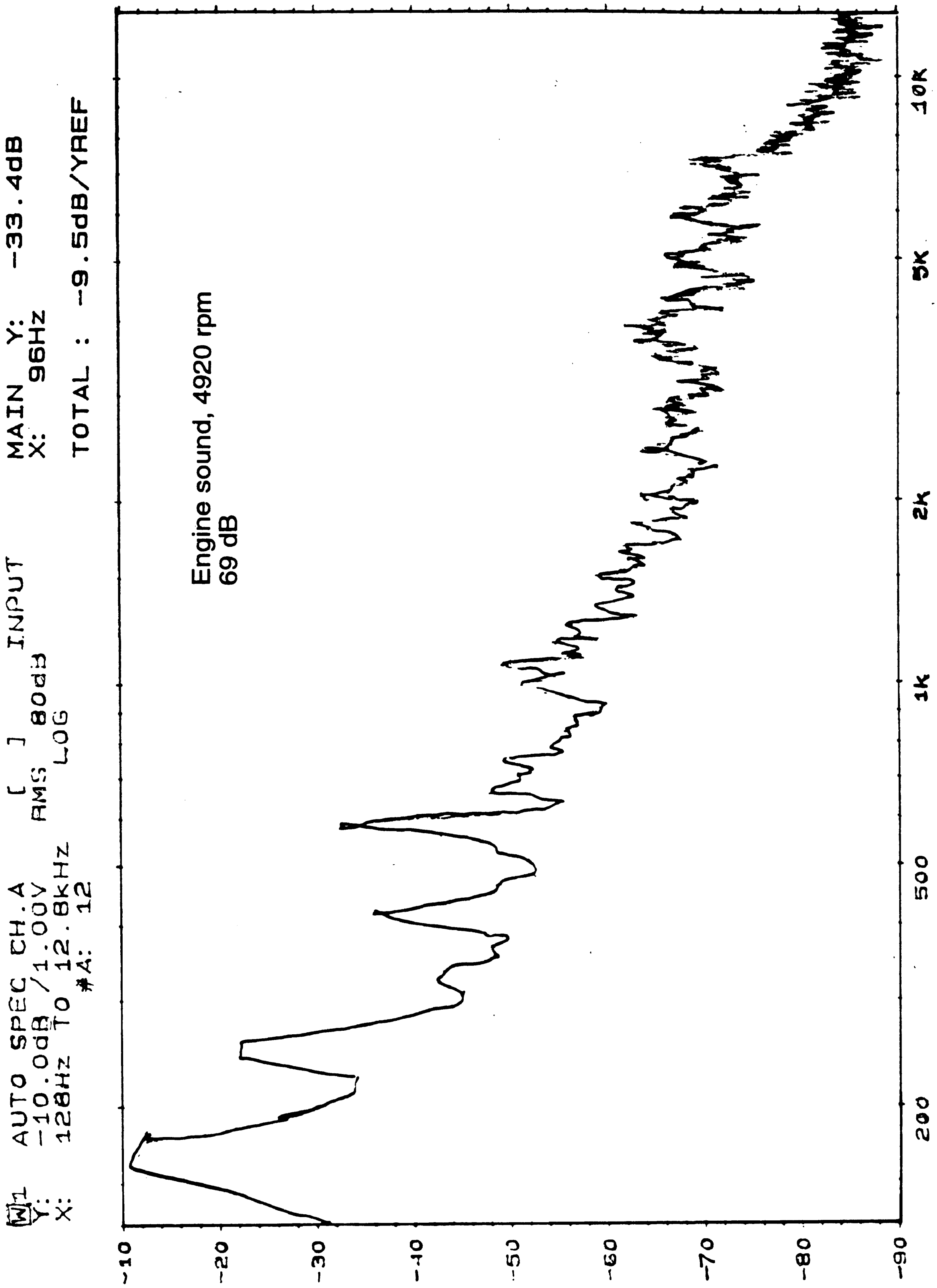


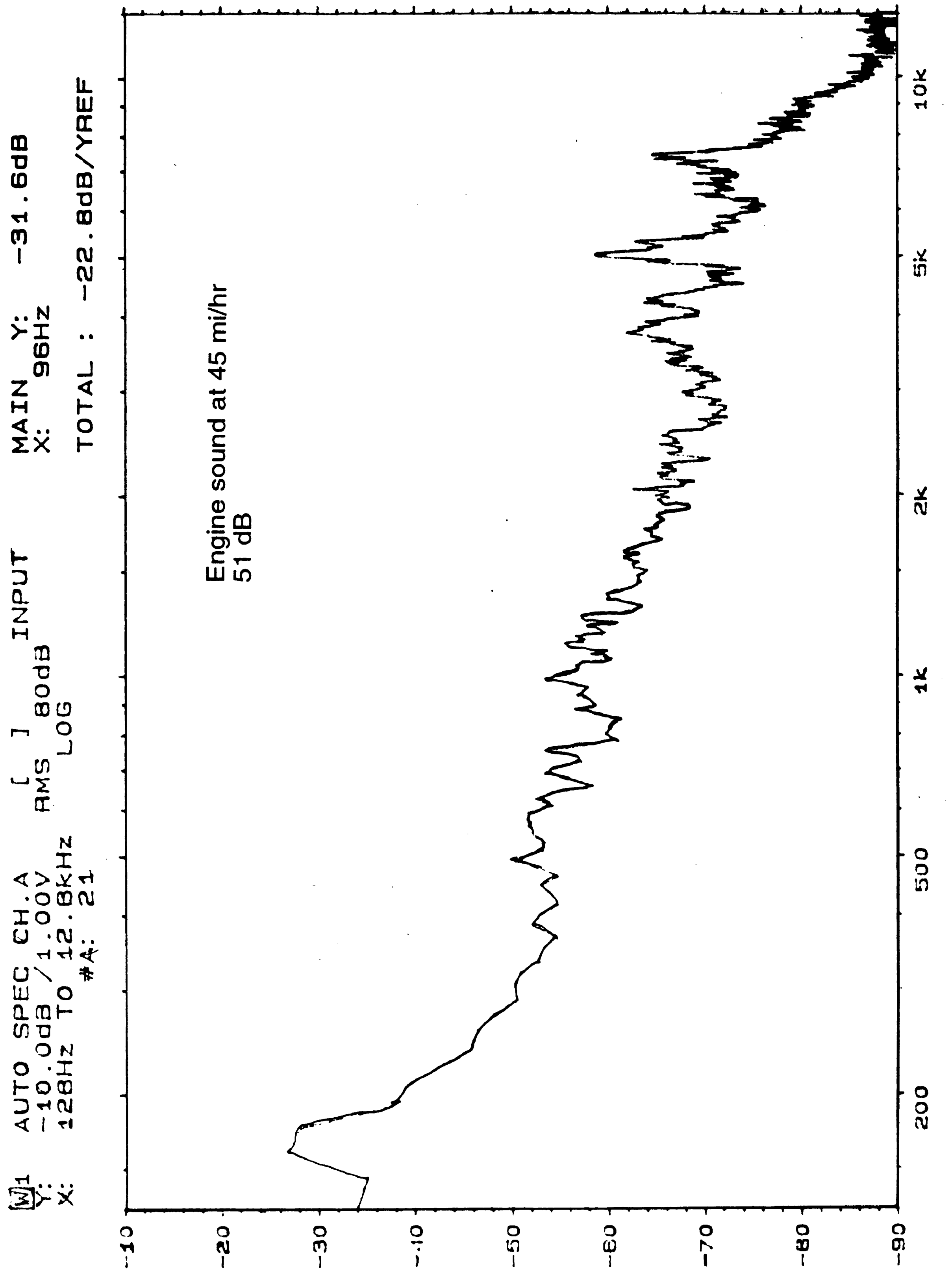
W1 AUTO SPEC CH.A [ ] INPUT
Y: -10.0dB /1.00V RMS 80dB
X: 128Hz TO 12.8kHz LOG
#A: 10
MAIN Y: -31.0dB
X: 96Hz
TOTAL : -21.8dB/YREF
Engine sound, 2030 rpm
56 dB
-10
-20
-30
-40
-50
-60
-70
-80
-90
200
500
1k
2k
5k
10k

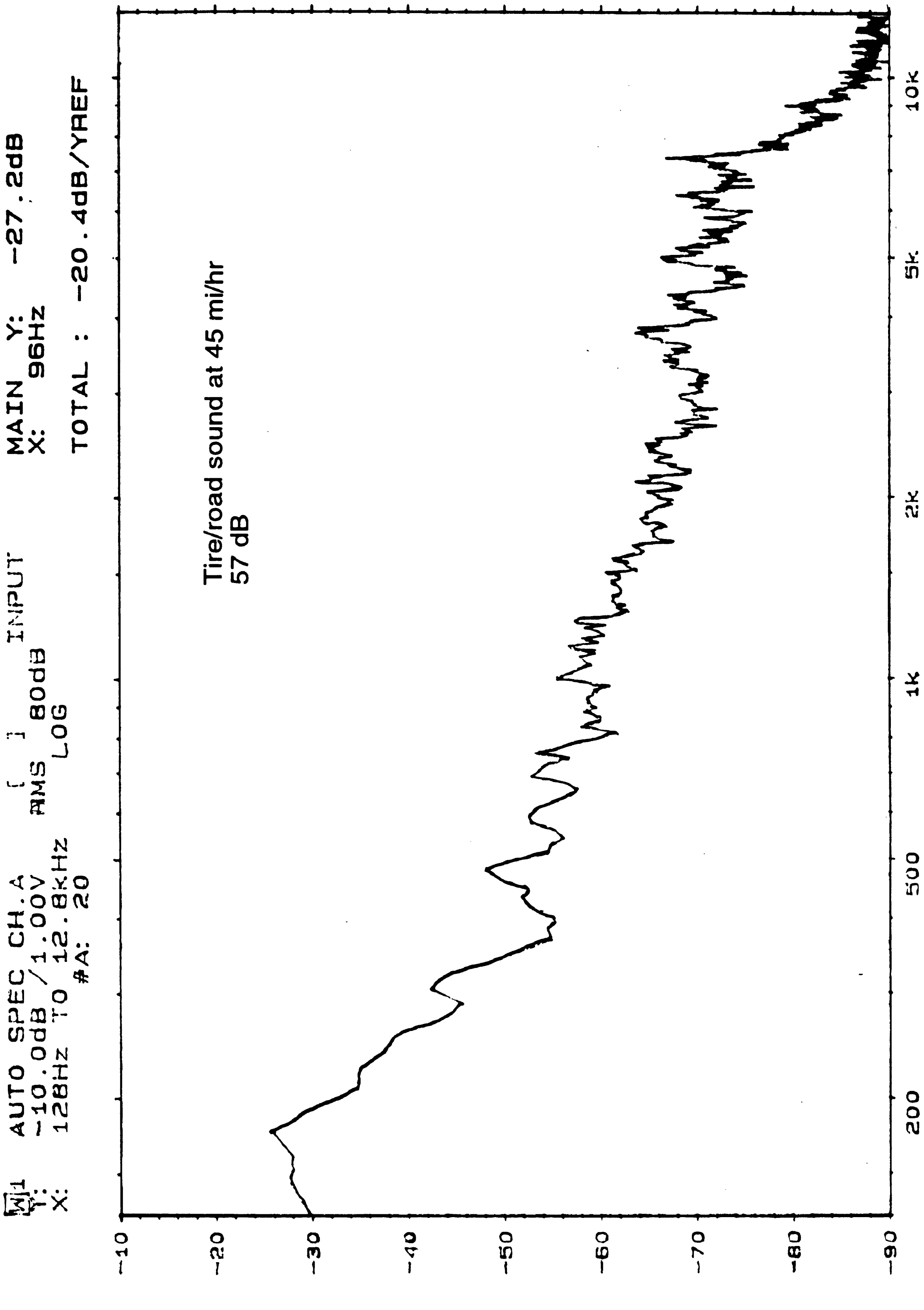

W1 AUTO SPEC CH.A
Y: -10.0dB /1.00V
X: 128Hz TO 12.8kHz
#A: 13
[ ]
RMS 80dB INPUT
LOG
MAIN Y: -15.7dB
X: 96Hz
TOTAL : -14.4dB/YREF
Engine sound, 2700 rpm
63 dB
-10
-20
-30
-40
-50
-60
-70
-80
-90
200
500
1k
2k
5k
10k

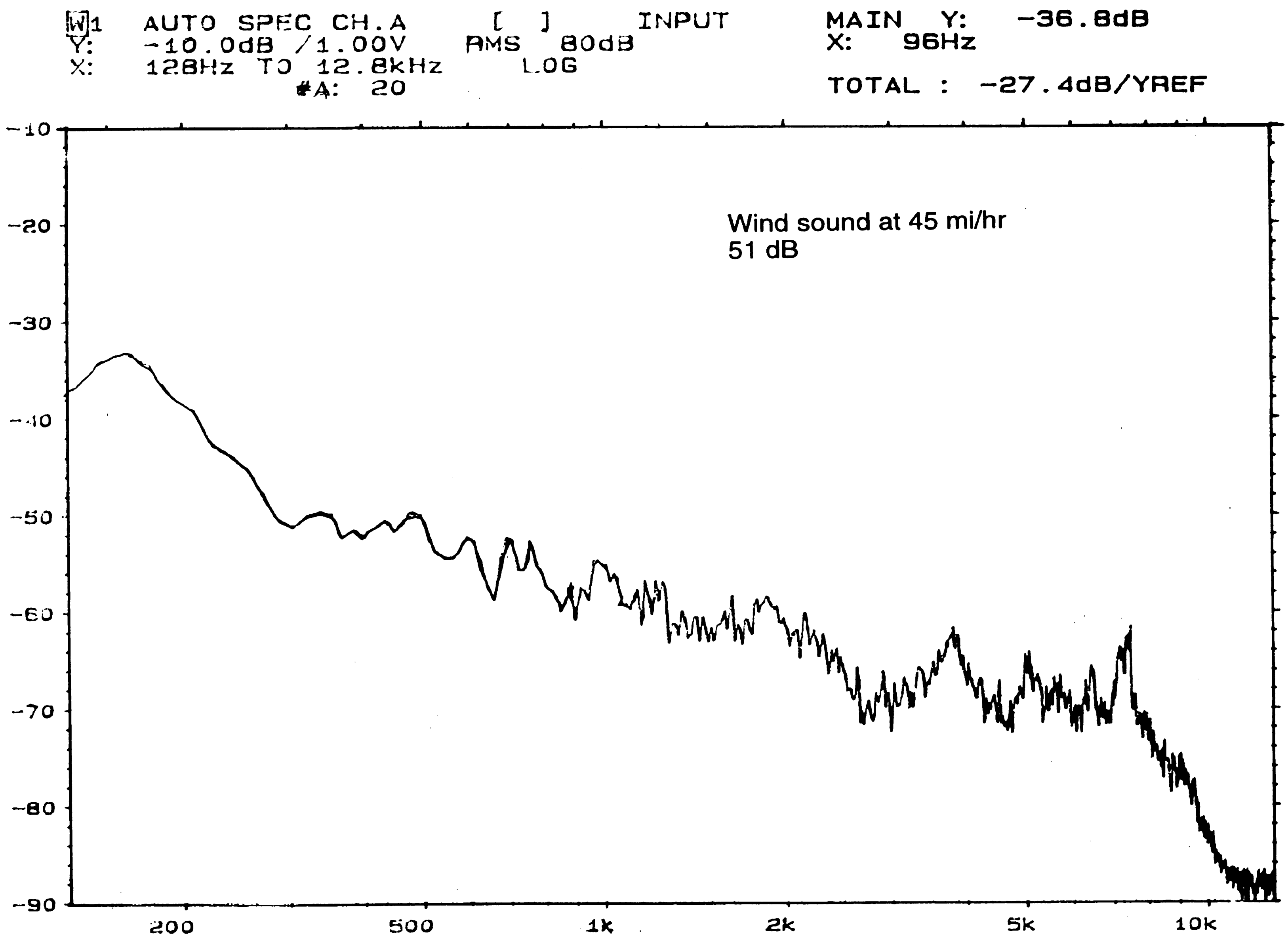

W1 AUTO SPEC CH.A [ ] INPUT
Y: -10.0dB / 1.00V RMS 80dB
X: 128Hz TO 12.8kHz LOG
#A: 11
MAIN Y: -26.0dB
X: 96Hz
TOTAL : -15.9dB/YREF
Engine sound, 3470 rpm
61 dB
-10
-20
-30
-40
-50
-60
-70
-80
-90
200
500
1K
2K
5K
10K

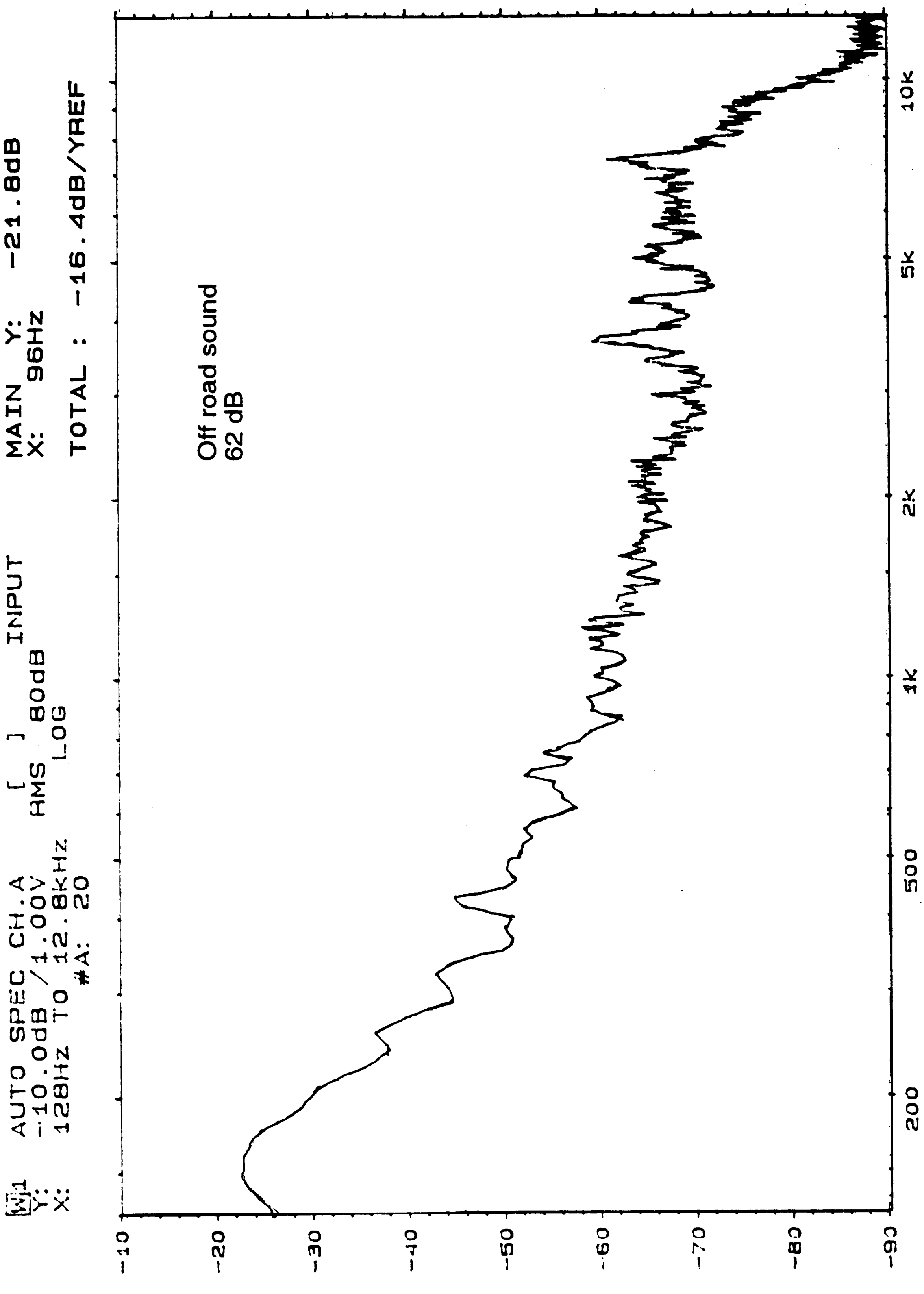

W1 AUTO SPEC CH.A [ ] INPUT
Y: -10.0dB /1.00V RMS 80dB
X: 128Hz TO 12.8kHz LOG
#A: 14
MAIN Y: -35.7dB
X: 96Hz
TOTAL : -8.9dB/YREF
Engine sound, 4230 rpm
66 dB
-10
-20
-30
-40
-70
-80
-90
200
500
1K
2K
5K
10K

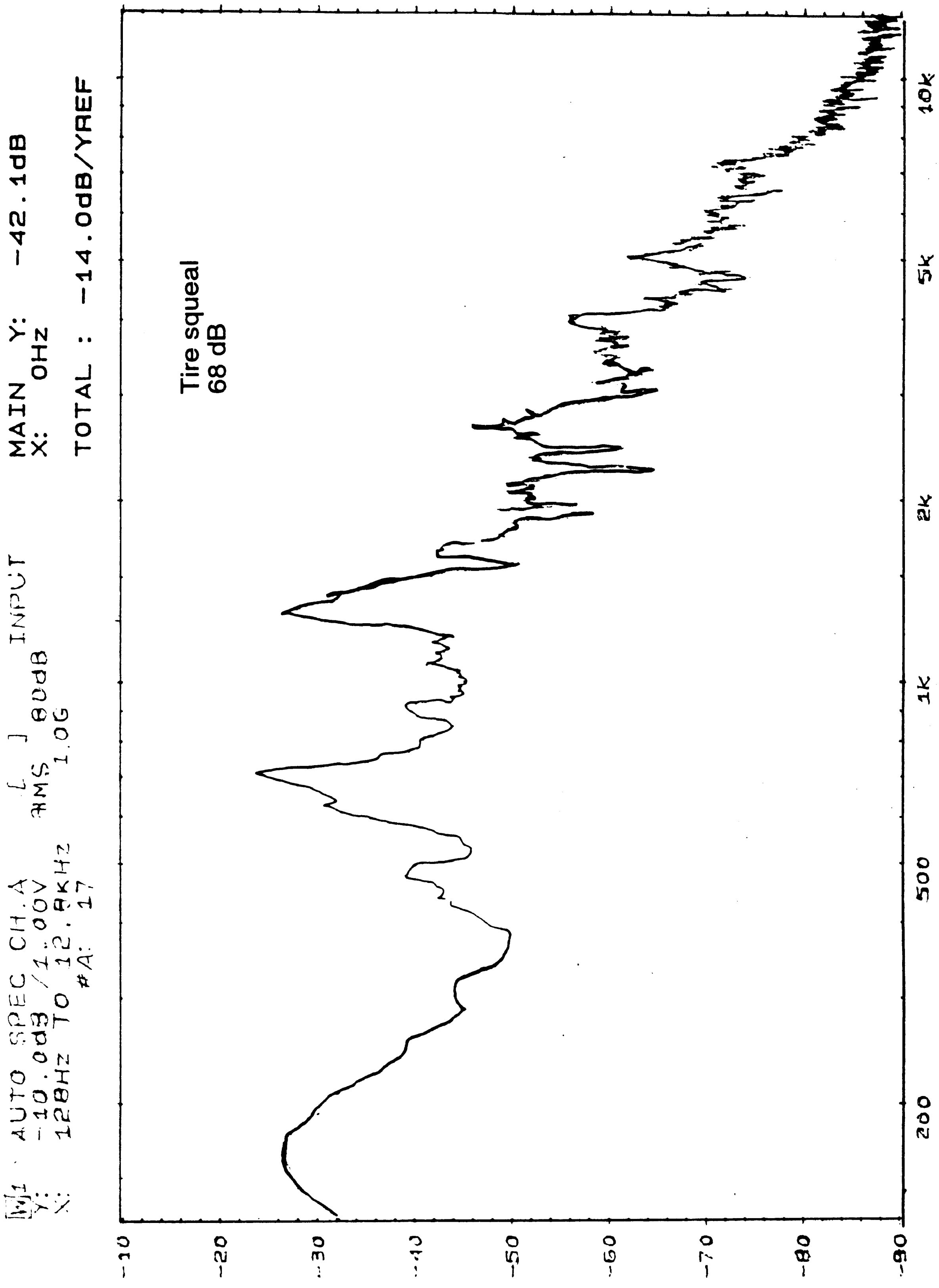

W1 AUTO SPEC CH.A [ ] MAIN Y: -33.4dB
Y: -10.0dB /1.00V RMS 80dB INPUT
X: 128Hz TO 12.8kHz LOG X: 96Hz
#A: 12
TOTAL : -9.5dB/YREF
Engine sound, 4920 rpm
69 dB
-10
-20
-30
-40
-50
-60
-70
-80
-90
200
500
1k
2k
5K
10K

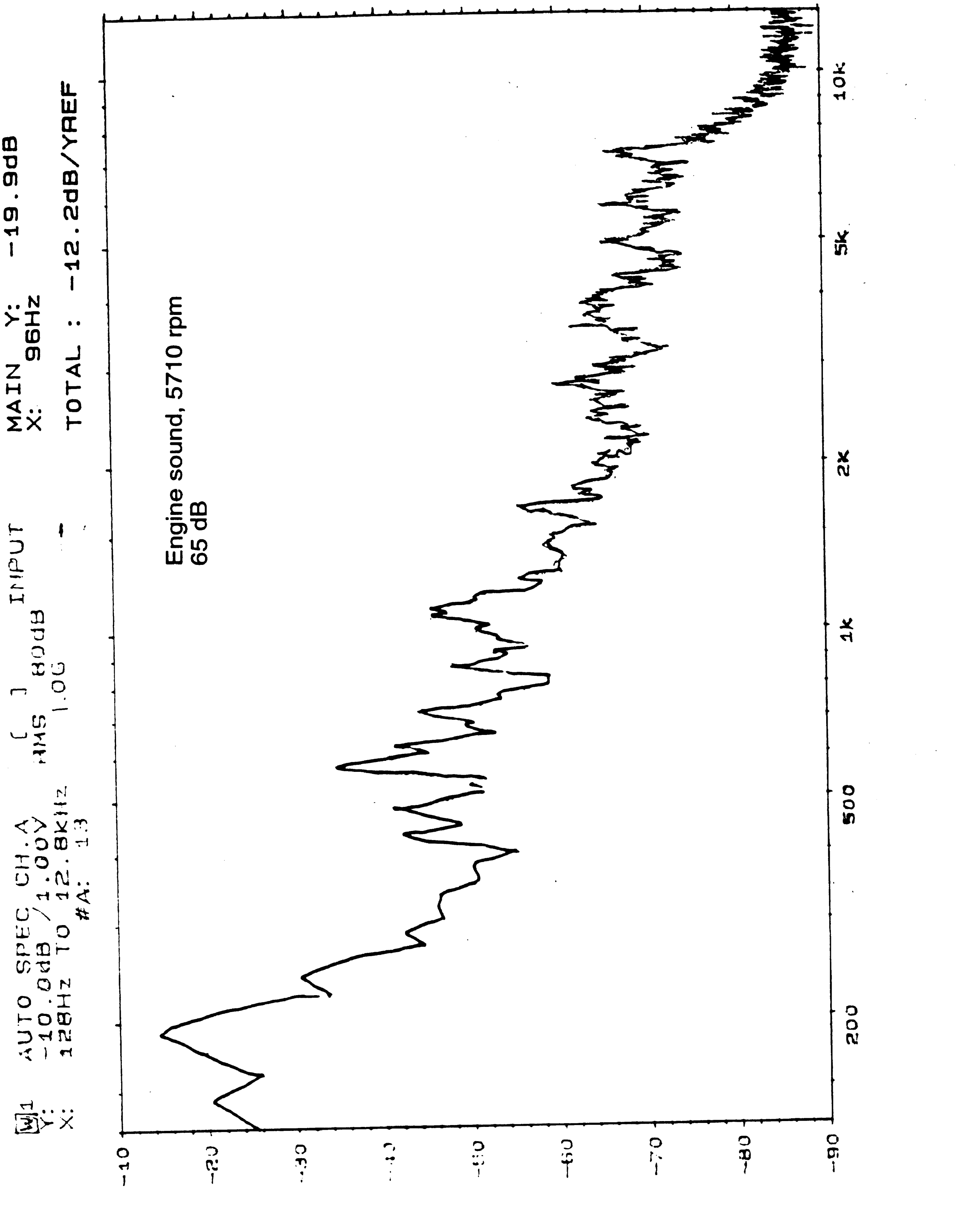

W1 AUTO SPEC CH.A [ ] INPUT MAIN Y: -31.6dB
Y: -10.0dB /1.00V RMS 80dB X: 96Hz
X: 128Hz TO 12.8kHz LOG TOTAL : -22.8dB/YREF
#A: 21
Engine sound at 45 mi/hr
51 dB
-10
-20
-30
-40
-50
-60
-70
-80
-90
200
500
1k
2k
5k
10k

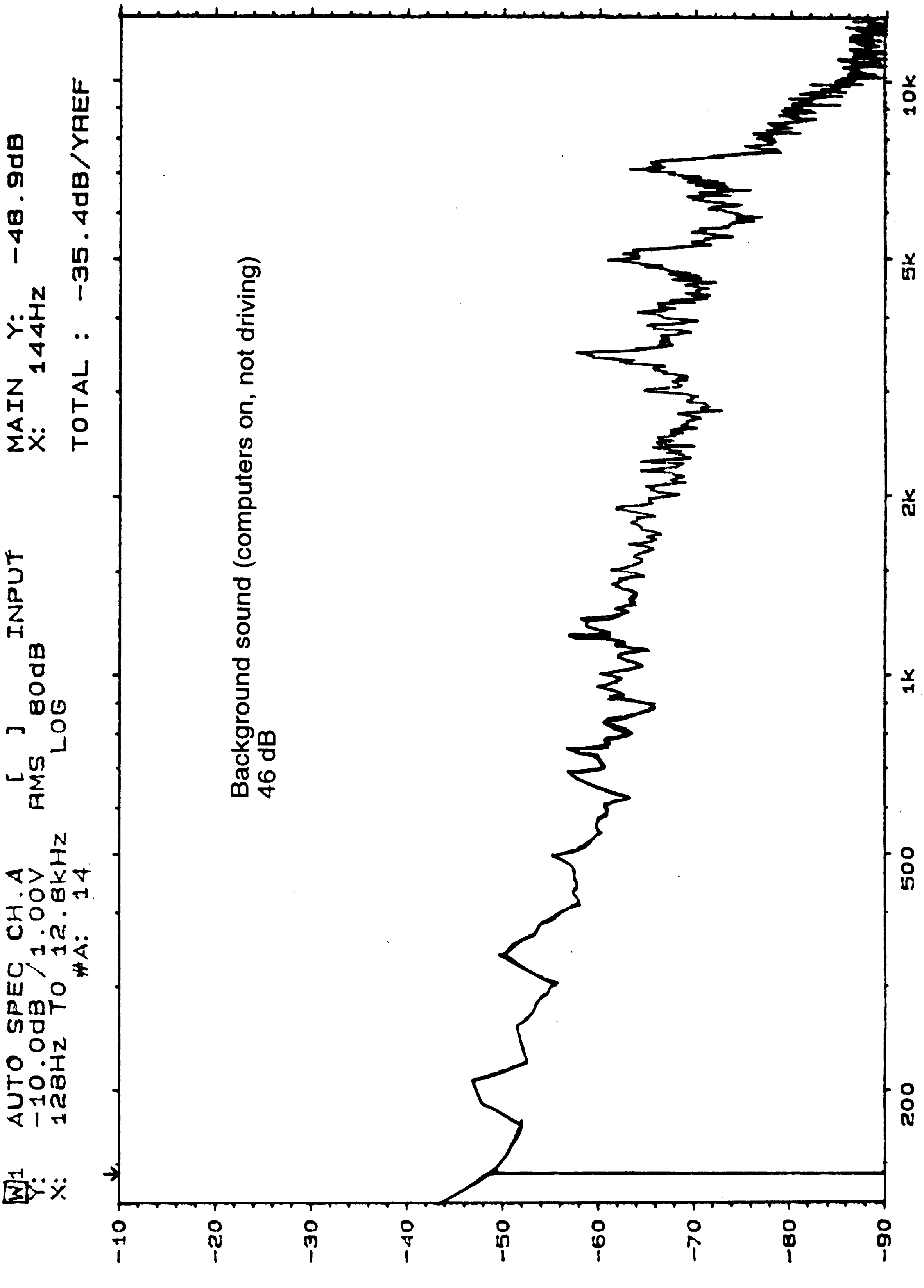

AUTO SPEC CH.A
-10.0dB /1.00V
128Hz TO 12.8kHz
#A: 20
RMS 80dB INPUT
LOG
MAIN Y: -27.2dB
X: 96Hz
TOTAL : -20.4dB/YREF
Tire/road sound at 45 mi/hr
57 dB
200
500
1k
2k
5k
10k
-10
-20
-30
-40
-50
-60
-70
-80
-90


W1 AUTO SPEC CH.A [ ] INPUT
Y: -10.0dB /1.00V RMS 80dB
X: 128Hz TO 12.8kHz LOG
#A: 20
MAIN Y: -36.8dB
X: 96Hz
TOTAL : -27.4dB/YREF
Wind sound at 45 mi/hr
51 dB
-10
-20
-30
-40
-50
-60
-70
-80
-90
200
500
1k
2k
5k
10k


AUTO SPEC CH.A [ ] INPUT
-10.0dB /1.00V RMS 80dB
128Hz TO 12.8kHz LOG
#A: 20
MAIN Y: -21.8dB
X: 96Hz
TOTAL : -16.4dB/YREF
Off road sound
62 dB
200
500
1k
2k
5k
10k
-10
-20
-30
-40
-50
-60
-70
-80
-90


AUTO SPEC CH.A
Y: -10.0dB /1.00V
X: 128Hz TO 12.8kHz
#A: 17
RMS 80dB
1.0G
INPUT
MAIN Y: -42.1dB
X: 0Hz
TOTAL : -14.0dB/YREF
Tire squeal
68 dB
-10
-20
-30
-40
-50
-60
-70
-80
-90
200
500
1k
2k
5k
10k


AUTO SPEC CH.A
Y: -10.0dB /1.00V
X: 128Hz TO 12.8kHz
#A: 13
RMS 80dB
INPUT
MAIN Y: -19.9dB
X: 96Hz
TOTAL : -12.2dB/YREF
Engine sound, 5710 rpm
65 dB
200
500
1k
2k
5k
10k
-10
-20
-30
-40
-50
-60
-70
-80
-90


W1 Y:
X:
AUTO SPEC CH.A
-10.0dB /1.00V
128Hz TO 12.8kHz
#A: 14
[ ]
RMS 80dB
LOG
INPUT
MAIN Y: -48.9dB
X: 144Hz
TOTAL : -35.4dB/YREF
Background sound (computers on, not driving)
46 dB
-10
-20
-30
-40
-50
-60
-70
-80
-90
200
500
1k
2k
5k
10k