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ACOUSTIC AND EMISSION CHARACTERISTICS OF SMALL, HIGH-SPEED INTERNAL COMBUSTION ENGINES

D. Morrison and R.V. Karsick

RICARDO CONSULTING ENGINEERS, LTD.
SUSSEX ENGLAND

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Washington DC 20590

PREFACE

This report addresses the acoustic aspects of small, internal combustion engines. The report has five technical sections, each of which focuses upon a particular study area of the program. The five sections are: Section, 2, Outdoor Noise Test Results from Saab 99GL and Peugeot 504GLD vehicles; Section, 3, Noise Tests on a Selection of European Passenger Vehicles: Section 4, Tests on a Saab B.I. 2-Liter Gasoline Engine; Section 5, Tests on a Peugeot 2.3-Liter Diesel Engine; and Section 6, An Urban Traffic Noise Model for High-Speed Gasoline and Diesel-Powered Light-Duty Vehicles.

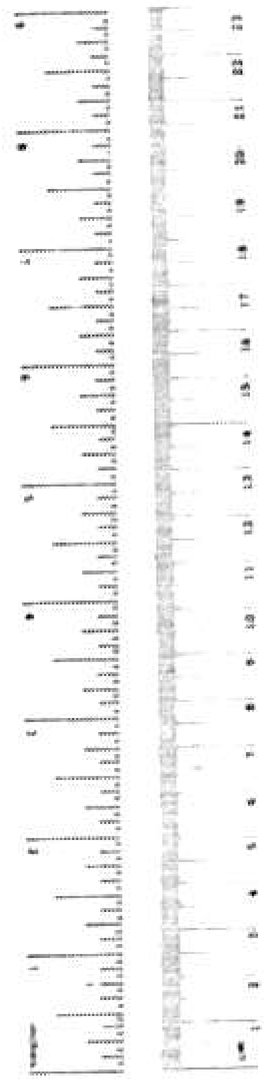
We would like to acknowledge the cooperation and contributions of all the subcontractors, Ricardo Consulting Engineers, Aerodyne Research, Inc., and A.D. Little, in the performance of this work. We would especially like to recognize the efforts of B.J. Challen and D. Morrison of Ricardo Consulting Engineers whose contributions were especially valuable throughout the program.

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

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



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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1. INTRODUCTION

This report addresses the acoustic aspects of small, internal combustion engines. The report consists of five technical sections, each of which focuses upon a particular study area of the program.

1.1 OUTDOOR NOISE TEST RESULTS FROM SAAB 99GL AND PEUGOT 504GLD VEHICLES

Section 2 of this report outlines the program of test work on the Saab 99GL and Peugeot 504GLD vehicles and summarizes the results obtained. The Saab and Peugeot vehicles, both in 1976 California build, were tested for drive-by noise over a comprehensive range of vehicle and engine operating conditions. Noise tests were also made with the vehicles stationary. Exhaust emissions and performance were also measured. The ISO drive-by noise level for the Saab was 79.1 dBA and for the Peugeot was 81.5 dBA. For the gasoline engine powered Saab, the major noise sources were the exhaust and engine, the intake and fan noise being insignificant. For the Peugeot, a diesel engine powered vehicle, the major noise sources were the engine and cooling fan, the intake and exhaust noise being negligible.

Increasing the load on the engine for a given engine speed by reducing the power/weight ratio increased the drive-by noise level on the Saab at certain critical engine speeds, largely because of the increased exhaust noise.

1.2 NOISE TESTS ON A SELECTION OF EUROPEAN PASSENGER CARS

Section 3 of this report describes a series of drive-by and interior noise tests that were carried out on a selection of European passenger cars. The tests covered a wide range of vehicle operating conditions. The cars tested were the Renault 4, Opel 2100D, Ford Fiesta, Ford Cortina 1600, Vauxhall Chevette GL, Chrysler Alpine 'S', Volvo 244 GL, Jaguar XJ6 4.2 and the Triumph

Dolomite Sprint. In addition, a Ricardo experimental turbocharged version of the Opel 2100D was also tested. The results of the previous tests on the Saab 99GL injection and Peugeot 504GLD were also used for comparison. On an ISO test basis, there was a spread of some 6dBA between the quietest and noisiest cars, the Triumph Dolomite Sprint being the highest ranking at 81.8 dBA (RHS, mean of two tests within 1dBA) and the Jaguar XJ6 being the lowest at 75.9 (LHS, mean of two tests). Averaging all the cars gave an overall ISO mean of 79.2 dBA.

Whereas there was no specific correlation between power/weight ratio and drive-by noise, if the cars were grouped broadly as small, medium and high performance luxury, there was a general trend of increasing ISO drive-by levels and decreasing interior noise with increasing size/performance.

The sound pressure levels were monitored at four microphone positions as the car was driven over a 20m test zone. The signals from these microphones together with vehicle position information were simultaneously recorded on a seven channel tape recorder.

Quantitative and qualitative assessments of the noise directionality were made by observation of the analog traces produced and by constructing polar noise contors for each vehicle. The value of the IDO test as a yard-stick for vehicle noise assessment is also commented on, with reference to the levels obtained from the other drive-by tests.

1.3 TESTS ON A SAAB B.I. 2-LITRE GASOLINE ENGINE

As part of a U.S. DOT program to assess high speed engine noise, tests were carried out for Calspan Corporation on a SAAB B.I. 2 litre gasoline engine under anechoic conditions. The results are presented in Section 4 of this report. Detailed baseline noise tests were made as well as performance and exhaust emission evaluations. The engine was in 1976 California emission build with manifold air oxidation, exhaust gas recirculation and fuel injection. The engine was removed from the SAAB 99GL car, which was the subject of the vehicle tests reported in Section 2.

1.4 TESTS ON A PUEGOT 2.3-LITRE DIESEL ENGINE

As part of a U.S. DOT program to assess high speee engine noise, tests were carried out for Calspan Corporation on a Peugeot 504GLD diesel engine in anechoic conditions. The results are presented in Section 5 of this report. Detailed noise measurements were made, and performance, economy, and emissions were also assessed over a range of operating conditions.

Over the whole of the speed and load range, noise, performance, economy, and emissions were typical of this type of engine. The maximum noise level to the sides of the engine was 101dBA at full load, rated speed operation. Maximum power produced was 47.5 kW at 75 rev/s (=4500 rev/min).

1.5 AN URBAN TRAFFIC NOISE MODEL FOR HIGH SPEED GASOLINE AND DIESEL POWERED LIGHT DUTY VEHICLES

Section 6 of this report presents a model of the noise generated by small, high speed engine-powered vehicles in a low density, i.e., non-continuous source, urban environment. This model facilitates the evaluation of the noise impact of these types of vehicles. This modeling, in order to fulfill its original objectives, should utilize to as great an extent as possible the information the engine/vehicle data generated earlier in this program. Consequently, unlike most traffic noise models, the emphasis of this modeling will be on the engine/vehicle system as opposed to propagation/interaction effects.

2. OUTDOOR NOISE TEST RESULTS FROM SAAB 99GL AND PEUGEOT 504GLD VEHICLES

2.1 INTRODUCTION

This report summarizes the emission, performance and noise tests carried out on the gasoline engine powered Saab 99 and the diesel engine powered Peugeot 504D.

A full, detailed report covering the entire High Speed Engines Project (including the 10 additional vehicle tests and the engine tests) will be issued on completion of the project.

The report concentrates on the noise tests and summarizes the results and conclusions of the wide matrix of drive-by tests, interior noise tests and exterior tests with the vehicle stationary.

2.2 TEST OBJECTIVES

The summarized objectives of this study were as follows (for the two selected vehicles, the Saab 99 and the Peugeot 504D):

a. To establish drive-by noise levels, using a four microphone array, over a wide matrix of vehicle and engine operating conditions (entry speed, gear ratio, acceleration rate, power:weight ratio) including tests to ISO R362 and SAE J986a procedure).

b. To identify and rank the vehicle noise sources on the basis of selected drive-by tests.

c. To measure polar noise distribution and identify noise sources with the vehicle stationary.

d. To measure interior noise levels at various operating conditions.

e. To establish the gaseous emissions characteristics and vehicle fuel economy on the basis of a standard test procedure over the LA4 driving cycle, including the effect on gaseous emissions of power:weight ratio (Saab only).

f. To measure the vehicle performance on the basis of maximum acceleration and vehicle speed.

2.3 TEST VEHICLES

The two baseline vehicles chosen as representative of typical European high-speed engine passenger cars were the Saab 99 and the Peugeot 504D. Both vehicles were standard production models, built for U.S. export to 1976 California emission standards. A brief specification of the vehicles is given in Table 2-1.* Both vehicles were run-in before testing.

2.4 TEST SITE

The test site for conducting the noise tests is shown schematically in Figure 2-1. The drive-by noise tests were conducted over the standard 20 m ISO test zone in all cases except for the SAE J986a test (15 m test zone). Due to the limited length of the test site, maximum speeds for the drive-by tests were restricted to 50 mile/h for the Saab and 30 mph for the Peugeot. The majority of the drive-by tests, however, were within these speed limits. For the few high speed drive-by tests, the testing facilities at the Motor Industries Research Association (MIRA), Nuneaton, were employed. The performance tests and interior noise tests were also carried out at MIRA.

2.5 INSTRUMENTATION

Four microphones were used to measure the instantaneous sound pressure level as the vehicle was driven through the 20 m test zone. The signal from each microphone was fed to a 7 channel FM tape recorder. The vehicle position on the track was determined by reference to seven vehicle position indicators (VPIs), these being photo-transistor relay switches, triggered from a sideways

*All figures and tables referred to in the text follow each section.

facing spotlight on the vehicle. (The diagrammatic layout of the microphones and vehicle position indicators is shown in Figure 2-1.) Pulse signals from the triggered vehicle position indicators were fed to the tape recorder. Also recorded was an engine speed signal, transmitted via an FM transmitter in the vehicle and received and converted at the control base through a frequency to voltage converter. The above mentioned signals occupied six of the seven channels, the seventh being utilized to record a synchronization pulse at the commencement of each run.

In order to provide an accurate read-out of the vehicle speed to the driver and also to enable the effect of load to be assessed (by varying the acceleration rate a known quantity for given entry speeds) a unique velocity/acceleration meter was devised. This instrument is fed by a frequency proportional to road speed which is generated by a magnetic pick-up adjacent to slots on the brake disc on a road wheel. For constant speeds, the system is calibrated for each road speed against the frequency generated from the slotted disc/pick-up, and the driver is able to drive the vehicle at a steady speed by maintaining a pointer on a center-zero meter at the zero position. For acceleration rates of a given rate a constantly increasing voltage is generated which is matched by accelerating the vehicle, thus maintaining a zero deflection on the center-zero meter.

2.6 OUTLINE DESCRIPTION OF VEHICLE

2.6.1 Drive-by Noise Tests

The drive-by noise test matrix for the Saab and Peugeot is tabulated in Table 2-2. The two matrices were arranged to be common to both vehicles as far as possible but due to performance limitation of the Peugeot some of the high speed, high acceleration tests were not possible. The drive-by tests were conducted by entering the 20 m zone at the prescribed speed and in the prescribed gear. After the front of the vehicle had crossed the zone start line the vehicle would be driven in one of the following modes; steady state, maximum acceleration (wide open throttle/full rack), an intermediate acceleration rate of 0.05 g, 0.1 g or 0.15 g (where possible), steady deceleration to halt after 20 m, and coasting (with clutch pedal depressed and the engine cut). Drive-by tests were also carried out with various major sources abated in order to identify and rank the sources on the basis of rolling noise, engine noise, exhaust noise, intake noise and fan noise.

The effect of power/weight ratio was also examined on the Saab by towing a 1 ton capacity trailer. The standard power/unladen weight ratio of the Saab was 0.04 bhp/lb and the Peugeot, 0.02 bhp/lb. Drive-by tests were carried out on the Saab for power/weight ratios of standard (0.04 bhp/lb), 0.03 and 0.02 bhp/lb.

2.6.2 Stationary Noise Tests

With the vehicle stationary, the following tests were conducted on both vehicles.

2.6.2.1 Polar Noise - The sound pressure level at 12 microphone positions around a 7.5m radius circle (centered on the mid-point of a line through the two VPI spotlights) was measured at various engine speeds to provide a comparison with the polar noise data extracted from the steady state drive-by tests.

2.6.2.2 Exhaust Noise Versus Engine Speed - The engine speed was increased steadily from idle to rated speed and the sound pressure level at four microphones around the vehicle recorded. The object of this test was to reveal any exhaust noise characteristics which might be critical in a drive-by test situation.

2.6.3 Interior Noise Tests

Interior noise recordings were made for various steady state speeds in top gear and also for the condition of accelerating from rest through the gears to 70 mile/h.

2.6.4 Performance Tests

The performance of each vehicle was assessed by timing maximum accelerations from rest to various speeds and by measuring the maximum speeds possible in each gear. For all these tests the vehicle was laden with a driver and passenger.

2.6.5 Exhaust Emission Tests

Both vehicles were emission tested for CO, HC and NO_x according to current Federal Register procedures over the LA4 cycle. In addition the Saab was tested at two further inertia values to simulate the effect of reducing the power/weight ratios. The inertias selected corresponded to power/weight ratios of 0.03 and 0.02 bhp/lb.

2.7 RESULTS AND DISCUSSION OF TESTS

2.7.1 Drive-by Noise Tests

2.7.1.1 Saab - The results of the standard ISO and SAE tests were as follows (the fan was off for these tests): (Figure numbers refer to trace samples)

			LHS	RHS
ISO (2nd gear, engry at 31 mile/h)	@ 7.5 m	Figure 46	79.1	78.6
SAE (1st gear, entry at 30 mile/h)	@ 7.5 m	Figure 47	85.2	83.5
" " "	@ 15 m		79.5	78.0
SAE (2nd gear, entry at 30 mile/h)	@ 7.5 m	Figure 48	76.9	76.9
" " "	@ 15 m		71.9	72.5

The Saab typically produced higher sound pressure levels to the left of the car than the right due to the rear left location of the exhaust tail pipe. The exhaust noise was also seen to be a critical factor in the drive-by tests, particularly at certain engine speeds, as was shown during the stationary tests (see Section 2.7.2.2).

The effect of gear ratio (i.e. engine speed) and vehicle speed on the drive-by maximum SPL is shown in Figure 2-2 for a series of steady state drive-bys. The rolling noise (coast-by) is shown as a baseline, for which a slope of 9.7 dB/octave was measured. In 3rd and top gears the additional contribution to the overall SPL above the rolling noise is small (1-2 dBA) and in 2nd gear is roughly of the same order as the rolling noise (i.e. +3 dB above the rolling noise). It is not until the engine is operating at abnormally high speeds (in 1st gear) when the overall SPL is significantly higher (~10-15 dBA above rolling noise). This will be shown to contrast significantly with the Peugeot results, where the engine noise was seen to be a dominant source, even in 3rd gear.

A detailed mapping of the drive-by noise was conducted by plotting the sound pressure level opposite the three microphones at 7.5 m (microphones 1, 2 and 3) against engine speed for various acceleration rates from 0 (steady state) to maximum for each of the four gears selected.

Thus for any given engine speed, the effect of load could be examined. These curves are shown in Figures 2-3 - 2-10. For 1st gear, Figures 2-3 and 2-4 show a considerable effect of load on the SPL, particularly at the lower end of the engine speed range. This will be shown later to be largely due to the effect of load on the exhaust noise. It is also known that gasoline engine noise can exhibit a greater sensitivity to load than a naturally aspirated diesel engine, where the effect of load is typically minimal (of the order 1 - 2 dBA). The results of the engine test bed work will help to clarify this load/noise effect. Figures 2-5 and 2-6 also show the load effect on drive-by, the effect being more pronounced on the left hand side (the exhaust side) in producing peaks at various engine speeds. The effect is similar for 3rd gear (Figures 2-7 and 2-8) but is not as easily apparent in top gear due to the limited amount of data available (small change in engine speed over the 20 m zone).

There was also some evidence that increasing the engine load by decreasing the power/weight ratio resulted in an increase in drive-by SPL for a given engine speed. This is shown clearly in Figure 2-11 in the engine speed region of 25 - 30 rev/s and 45 -50 rev/s (later shown by the stationary test to be critical regions from the exhaust noise aspect). The best fit curves though the test points for each power/weight ratio test was obtained using a Polynomial Curve-Fit computer program.

Noise source tests were analyzed for the two conditions of 30 mile/h steady state, 2nd gear and 30 mile/h entry, maximum acceleration, 2nd gear. The overall results are shown in Figure 2-12. From tests with a sound level meter around the air cleaner it was concluded that the intake noise was insignificant. Silencing the exhaust resulted in a considerable reduction in drive-by noise under maximum acceleration conditions (>3 dB). The fan noise was impossible to detect during a drive-by test. The fan on the Saab was electrically driven, provision having been made to override the thermostat such that tests could be made with the fan on or off. Figure 2-13 shows the percentage breakdown of the three major noise sources, rolling, engine and exhaust. The significance of the exhaust noise to the left of the vehicle is readily apparent. Figure 2-14 shows the same results but plotted on the basis of constant rolling noise.

Frequency spectra for the two drive-by conditions are shown in Figure 2-15; 30 mile/h entry speed, 2nd gear maximum acceleration and steady state. The spectra are maxima for a particular drive-by. The characteristic increase in low frequency noise with increase in load on gasoline engines is clearly shown in these A-weighted spectra, and in fact dominate the maximum acceleration (i.e. maximum load) spectra.

Drive-by spectra for the noise source tests are shown in Figures 2-16 and 2-17 (left hand side only). The relative insignificance of the fan noise is apparent and also the substantial reduction in the low-mid frequency range noise with the exhaust silenced.

From the steady state drive-by tests, it was possible to construct polar noise plots from analysis of he noise characteristics during the drive-by with reference to the geometry of the four microphones and the seven VPIs, and correcting the SPL to that expected at 7.5 m (based on the inverse square law). A typical plot is shown in Figure 2-18 for 30 mile/h, 2nd gear. The most apparent feature of the noise distribution is the peak caused by the exhaust noise. Otherwise, there is little fluctuation of SPL from the 72.5 dBA 'contour'. Figure 2-19 shows an extreme case where the dominant source is the engine (50 mile/h. 2nd gear) and the plot is more regularly circular. The polar plot derived from the steady state tests was also used to examine the noise source tests at 30 mile/h, 2nd gear. Figure 2-20 shows four polar curves indicating the relative significance (above the rolling noise baseline) of the exhaust and engine noise.

2.7.1 2 Peugeot - The results obtained from the Peugeot tests are presented below in a similar manner to those for the Saab.

The results of the standard ISO and SAE tests were as follows: (Figure numbers refer to trace samples)

			LHS	RHS
ISO (2nd gear, entry at 28 mile/h)	@ 7.5 m		81.5	81.0
SAE (2nd gear, entry at 30 mile/h)	@ 7.5 m	Figure 2-49	83.1	82.7
" " "	@ 15 m	Figure 2-50	77.7	77.0

The fan was off for these tests.

Figure 2-21 shows the effect of gear ratio and vehicle speed on SPL (corresponding to Figure 2-2). Apart from top gear, the engine noise is shown here to cause a significant increase above the rolling noise, and more pronounced than for the Saab. The slope of the coast-by noise is similar (as might be expected as both cars have similar weights and tire sizes) at 9.4 dBA/octave.

Figures 2-22 - 2-29 (corresponding to Figures 2-3 - 2-10) show the effect of load on drive-by noise and it is clearly shown that the Peugeot load/noise characteristics differ widely from the

Saab. In all four gears, there is only slight indication of increasing load increasing the drive-by noise level and in most cases the results from all the steady-state and acceleration tests for a given engine speed and gear fall within the expected range of experimental scatter. It will be shown later that not only was the exhaust noise insignificant on the Peugeot but that the exhaust noise displayed no peaks at particular engine speeds as was so striking on the Saab.

The noise source breakdown is shown in Figure 2-30 where it is clear that the engine noise is the dominant source for both the acceleration and steady state tests, with the fan showing up as a significant source during the steady state test. The fan, a 13 in. diameter, 8 bladed unit, was driven at engine speed via an electromagnetic clutch, operated by a coolant temperature switch in the radiator. This switch was by-passed in order to carry out tests with and without the fan operative. With the fan engaged, the tonal noise characteristic was clearly audible at high engine speeds as the vehicle entered the test zone (i.e. observer facing the vehicle front). The high noise level from the fan to the front of the vehicle is evident from the polar noise distribution (see Figure 2-38). Figure 2-31 shows the noise source percentage breakdown, and Figure 2-32 the same results but expressed on a basis of constant rolling noise. The exhaust and intake noise sources were insignificant.

Maximum spectra for the two-drive-by conditions of 30 mile/h entry, maximum acceleration and steady state are shown in Figure 2-33. The maximum acceleration spectra show a significant increase in SPL in the 125 Hz third octave band and a general slight increase over the remainder of the spectrum; the shape of the maximum acceleration and steady state spectra are otherwise broadly similar. Figures 2-34 and 2-35 show the source contributions for the two drive-by conditions above. As has been shown already, for the maximum acceleration condition, the dominant source was the engine noise with all other sources contributing very little in addition. This is seen clearly in Figure 2-35, although a slight peak in the 630 Hz third octave band is apparent with the fan on. This peak is more striking in Figure 2-34 for the steady state case and identifies the fan as a significant source, even when this maximum spectrum occurred with the vehicle approximately opposite the measuring microphone. The peak over the 500 - 630 Hz bandwidths corresponds to the blade passing frequency of the fan at this engine speed (8 blades x 62 rev/s = 496 Hz). The SPL scatter over the high frequencies from source test to source test indicates the degree of repeatability of drive-by testing.

The coast-by spectrum, shown in Figure 2-34 compares very well with the coast-by spectrum for the Saab (Figure 2-16) again generally indicating the similar coast-by noise characteristics of the two vehicles.

Figures 2-36 and 2-37 show typical polar noise plots. No particular peaks are evident, as was for the case of the Saab exhaust noise. These tests, however, were with the fan off. The polar noise plots for the noise sources, shown in Figure 2-38 clearly show the effect of the fan noise to the front of the vehicle.

2.7.2 Stationary Noise Tests

2.7.2.1 Polar Noise - The polar noise distribution with the vehicle stationary is shown in Figure 2-39 for the Saab, and Figure 2-40 for the Peugeot. Reasonable agreement between the two tests for the respective vehicles is evident (except that the relatively coarse microphone array for the stationary tests does not detect the finer peaks displayed by the drive-by polar plot analysis).

2.7.2.2 Exhaust Noise Versus Engine Speed - Figure 2-41 shows the effect of engine speed on the SPL to the sides of the Saab (mics 1 and 2), the front (mic 3) and rear (mic 4). The microphone positions are shown in Figure 2-42. The critical nature of the exhaust noise with engine speed is clearly shown at the mic 4 position, closest to the exhaust. Peak fluctuations of 6 - 9 dBA are evident, and over a very small engine speed range. Such critical exhaust characteristics give rise to considerable variations in drive-by noise, and are also affected by engine load, as was apparent from the drive-by curves (Figures 2-3 - 2-10).

By contrast, Figure 2-43 shows the results of the same test for the Peugeot, where in this case not only is there a complete absence of such critical speed regions, but the SPL opposite the engine (mic 3) is greater than that opposite the exhaust at a given engine speed (confirming the results of the drive-by test where the exhaust noise was shwon to be insignificant).

2.7.3 Interior Noise Tests

Figure 2-44 summarizes the interior noise tests for the Saab. The trace indicates the internal noise level at the driver's ear position as the vehicle is accelerated through the gears at wide open throttle. On the same curve are shown the interior noise levels for various steady state cruise conditions in top gear. Figure 2-45 shows the results from corresponding tests on the Peugeot. Over the top gear cruising range from 20 - 70 mile/h, the Peugeot interior noise is some 2 1/2 - 4 1/2 dBA greater than that of the Saab.

2.7.4 Performance Tests

A summary of the results of the performance tests is given below:

	Saab	Peugeot
Acceleration Tests:		
0-20 mile/h	3.6 s	3.7 s
0-30 mile/h	5.5 s	7.0 s
0-40 mile/h	8.2 s	9.7 s
0-50 mile/h	11.2 s	16.0 s

Acceleration Tests:	Saab	Peugeot
0-60 mile/h	14.8 s	20.6 s
standing start 1/4 mile	19.5s	22.2 s
maximum speed (top gear)	105 mile/h	85 mile/h

2.7.5 Exhaust Emissions Tests

The summarized results of the exhaust emissions tests were as follows:

	HC	NOx	CO	Fuel cons. mile/US gall.*
Saab (standard)	0.91	1.5	7.1	17.3
Saab (0.30 bhp/lb equivalent inertia)	0.93	1.8	8.0	16.7
Saab (0.02 bhp/lb equivalent inertia)	1.1	2.2	9.3	16.2
Peugeot (standard)	0.59	1.1	1.4	28.6

*over LA4 cycle

TABLE 2-1. BRIEF SPECIFICATION OF VEHICLES

	SAAB 99	PEUGEOT 504D
Engine type	gasoline, naturally aspirated	indirect injection diesel, naturally aspirated
Engine capacity	1.985 L (121 in^3)	2.112 L (129 in^3)
Nominal max power	110 bhp	65 bhp
Nominal max engine speed	5500 rev/min	4500 rev/min
Weight as tested for drive-by tests	2780	3260
Weight as tested for performance tests	3120	3440
Emission build standard	California 1976	California 1976
Fuel injection system	Bosch (Continuous Injection)	CAV (Rotodiesel)
Transmission	4 forward ratios, manual	4 forward ratios, manual

TABLE 2-2. CALSPAN HSE PROJECT: SAAB 99 AND PEUGEOT 504D DRIVE-BY TEST SCHEDULE

ENTRY SPEED MILE/H	GEAR	ACCEL.	S = SAAB	P = PEUGEOT	COMMENTS
20	4	Steady Speed	S	P	
30	4	"	S	P	
40	4	"	S	P*	
50	4	"	S		
20	3	"	S	P	
30	3	"	S	P	
40	3	"	S	P*	
50	3	"	S		
10	2	"		P	
20	2	"	S	P	
30	2	"	S	P	
40	2	"	S		
50	2	"	S		
10	1	"		P	
20	1	"	S	P	
30	1	"	S		
20	4	MAX	S	P	
30	4	"	S	P	
40	4	"	S	P*	
20	3	"	S	P	
30	3	"	S	P	
4[illegible]	3	"	S	P*	
10	2	"	S	P	

*only LHS possible due to performance limitations

TABLE 2-2. CALSPAN HSE PROJECT: SAAB 99 AND PEUGEOT 504D DRIVE-BY TEST SCHEDULE (CONTINUED)

ENTRY SPEED MILE/H	GEAR	ACCEL.	S = SAAB	P = PEUGEOT	COMMENTS
20	2	MAX	S	P	
30	2	"	S	P	Also over SAE 15 m test zone
31	2	"	S		
28	2	"		P	
40	2	"	S		
10	1	"	S	P	
20	1	"	S	P	
30	1	"	S		Also over SAE 15 m test zone for Saab
40	3	0.15g	S		These tests not possible with Peugeot
20	3	"	S		
40	2	"	S		
20	2	"	S		
10	2	"	S		
20	1	"	S		
10	1	"	S		
40	4	0.10g	S		
20	4	"	S		
40	3	"	S		
30	3	"	S	P	
20	3	"	S	P	
40	2	"	S		
30	2	"	S		
20	2	"	S		
10	2	"	S	P	
20	1	"	S		
10	1	"	S	P	

TABLE 2-2. CALSPAN HSE PROJECT: SAAB 99 AND PEUGEOT 504D DRIVE-BY TEST SCHEDULE (CONTINUED)

ENTRY SPEED MILE/H	GEAR	ACCEL.	S = SAAB	P = PEUGEOT
40	4	0.05g	S	P*
20	4	"	S	P
40	3	"	S	P*
30	3	"	S	P
20	3	"	S	P
40	2	"	S	
30	2	"	S	P
20	2	"	S	P
10	2	"	S	P
20	1	"	S	P
10	1	"	S	P

ENTRY SPEED MILE/H	GEAR	ACCEL.	POWER/WT bhp/lb	S = SAAB
30	2	0.10g	0.02	S
20	2	"	"	S
10	2	"	"	S
20	1	"	"	S
10	1	"	"	S
30	2	0.05g	0.02	S
20	2	"	"	S
10	2	"	"	S
20	1	"	"	S
10	1	"	"	S
30	2	0.15g	0.03	S
20	2	"	"	S
10	2	"	"	S
20	1	"	"	S
10	1	"	"	S

*only LHS possible due to performance limitations

TABLE 2-2. CALSPAN HSE PROJECT: SAAB 99 AND PEUGEOT 504D DRIVE-BY TEST SCHEDULE (CONTINUED)

ENTRY SPEED MILE/H	GEAR	ACCEL.	POWER/WT bhp/lb	S - SAAB P - PEUGEOT
30	2	0.10g	0.03	S
20	2	"	"	S
10	2	"	"	S
20	1	"	"	S
10	1	"	"	S
30	2	0.05g	0.03	S
20	2	"	"	S
10	2	"	"	S
20	1	"	"	S
10	1	"	"	S
40	N (Engine cut)	Coast		S P*
30	N	"		S P
20	N	"		S P
40	4	Steady decel braking to stop at end of test zone		S P
30	3			S P
20	2			S P
10	1			P
NOISE SOURCE TESTS			BUILD	
30	2	Const. Speed	Exhaust Silenced Fan off	S P
30	2	"	Fan on Normal Build	S P
31**	2	MAX	Exhaust Silenced Fan off	S P
31**	2	MAX	Fan on Normal Build	S P

*not possible due to performance limitations

** 30 mile/h for Peugeot

TABLE 2-2. CALSPAN HSE PROJECT: SAAB 99 AND PEUGEOT 504D DRIVE-BY TEST SCHEDULE (CONTINUED)

ENTRY SPEED MILE/H	GEAR	ACCEL.	BUILD	S = SAAB P = PEUGEOT
30	2	Const. Speed	Intake Silenced Fan off	P
30	2	MAX	"	P
28	2	"	"	P
28	2	"	Exhaust Silenced Fan off	P
28	2	"	Normal Build Fan on	P

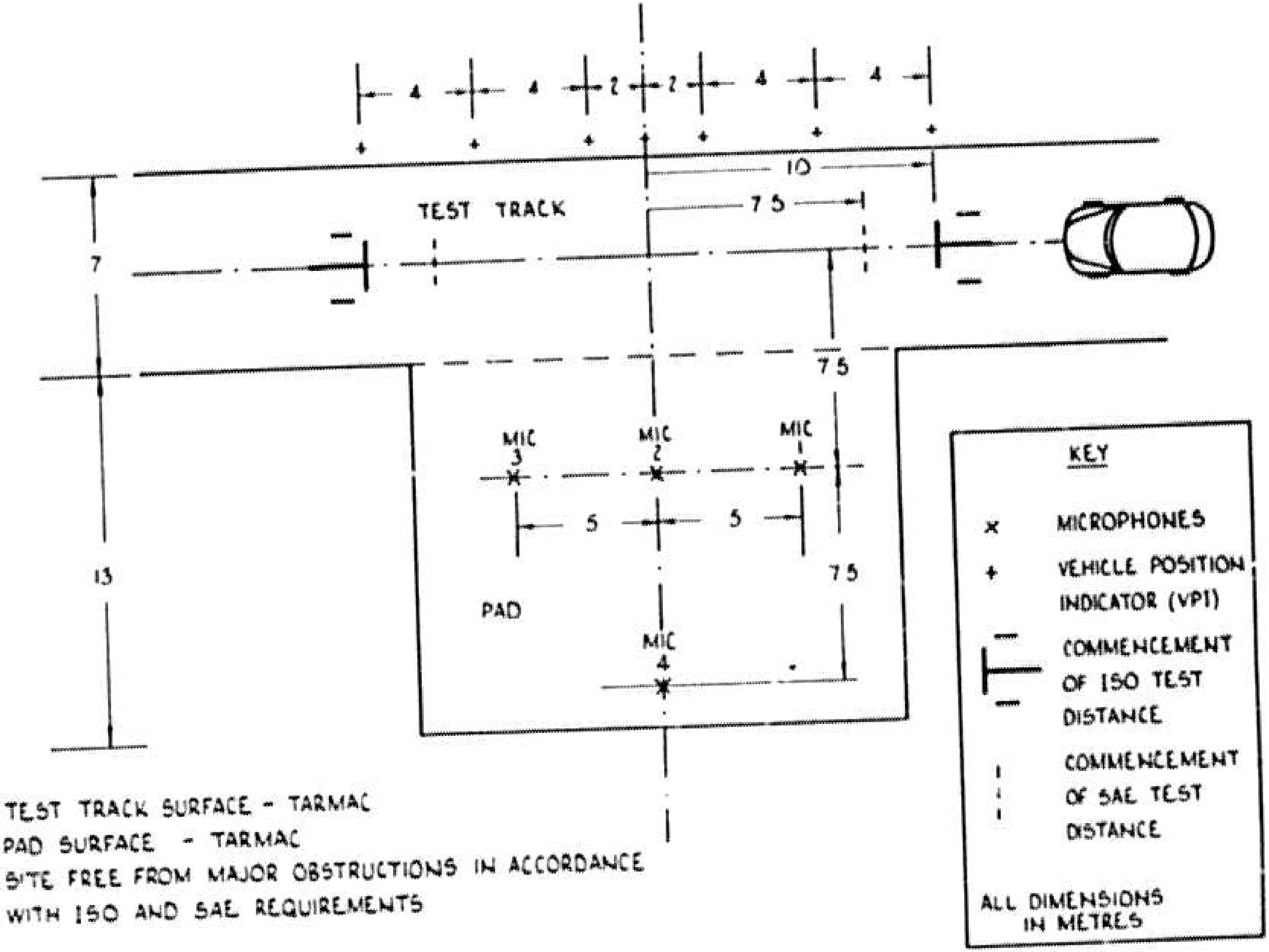


FIGURE 2-1. RICARDO DRIVE-BY NOISE TEST SITE

LEFT SIDE

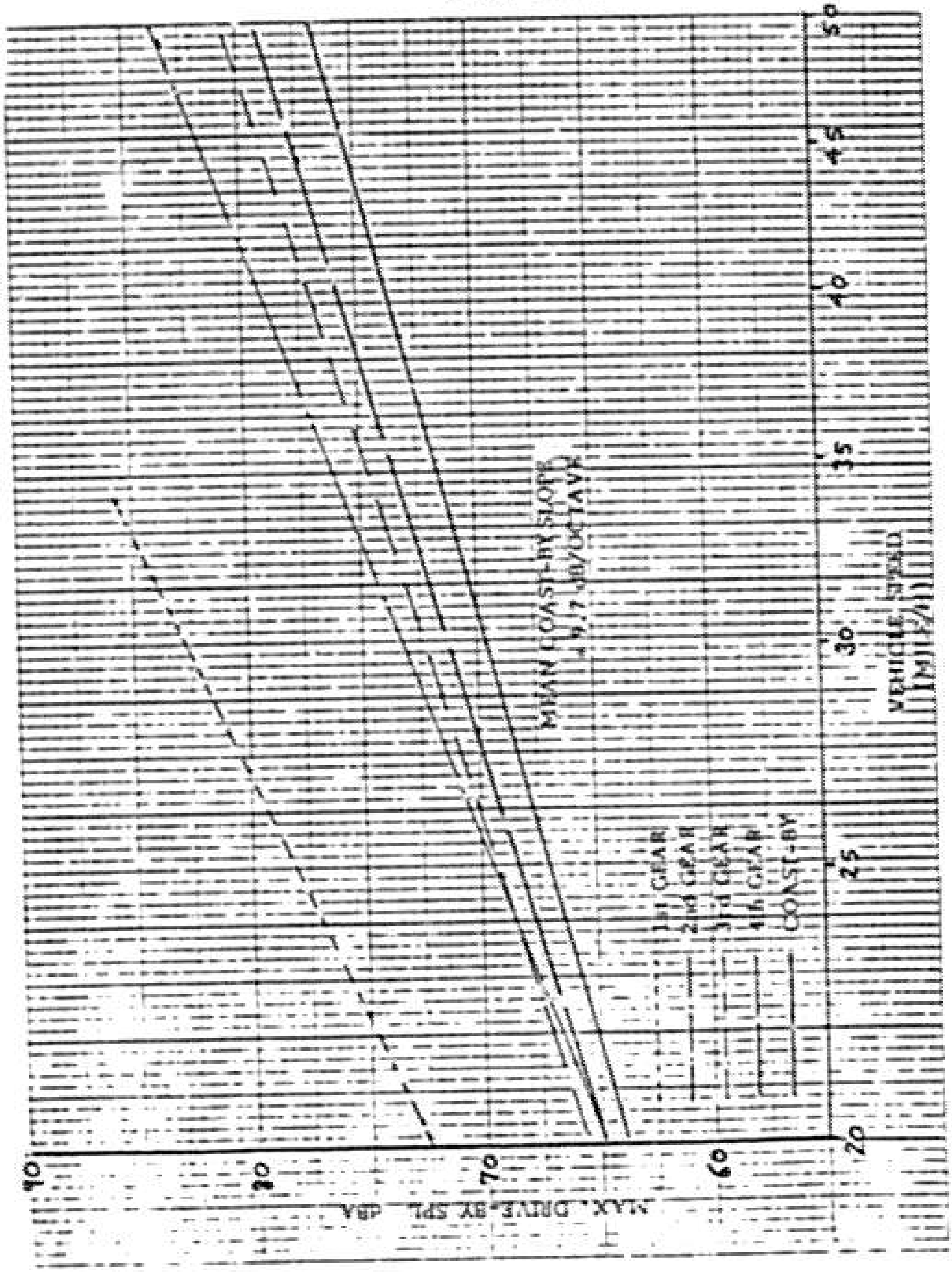


FIGURE 2-2. SAAB - EFFECT OF VEHICLE SPEED AND GEAR GEAR RATIO ON MAXIMUM DRIVE-BY SPL FOR STEADY STATE TESTS (INCLUDING COAST-BY)

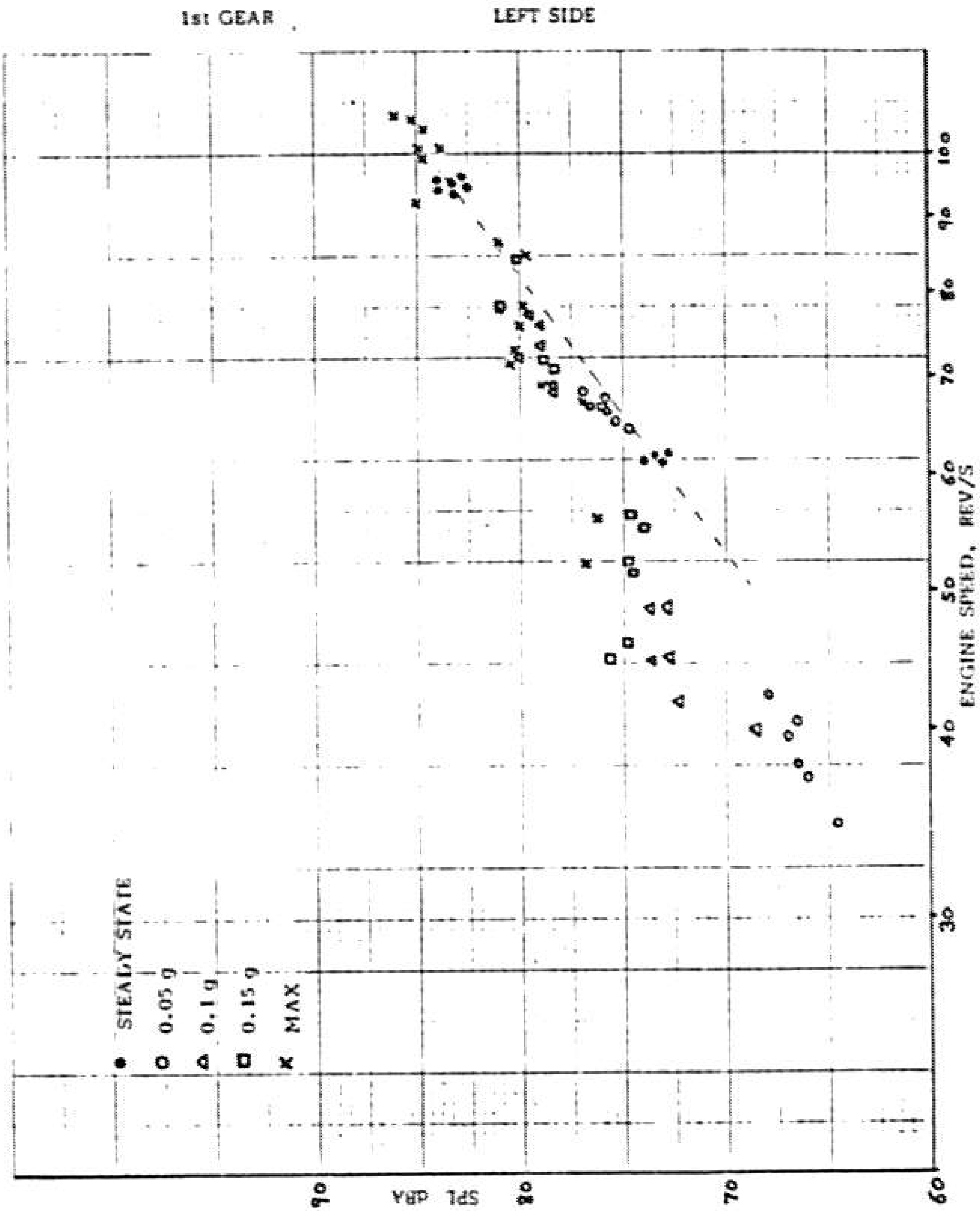


FIGURE 2-3. ENGINE SPEED V SPL OPPOSITE MICS. 1,2 AND 3 AT VARIOUS ACCELERATION RATES

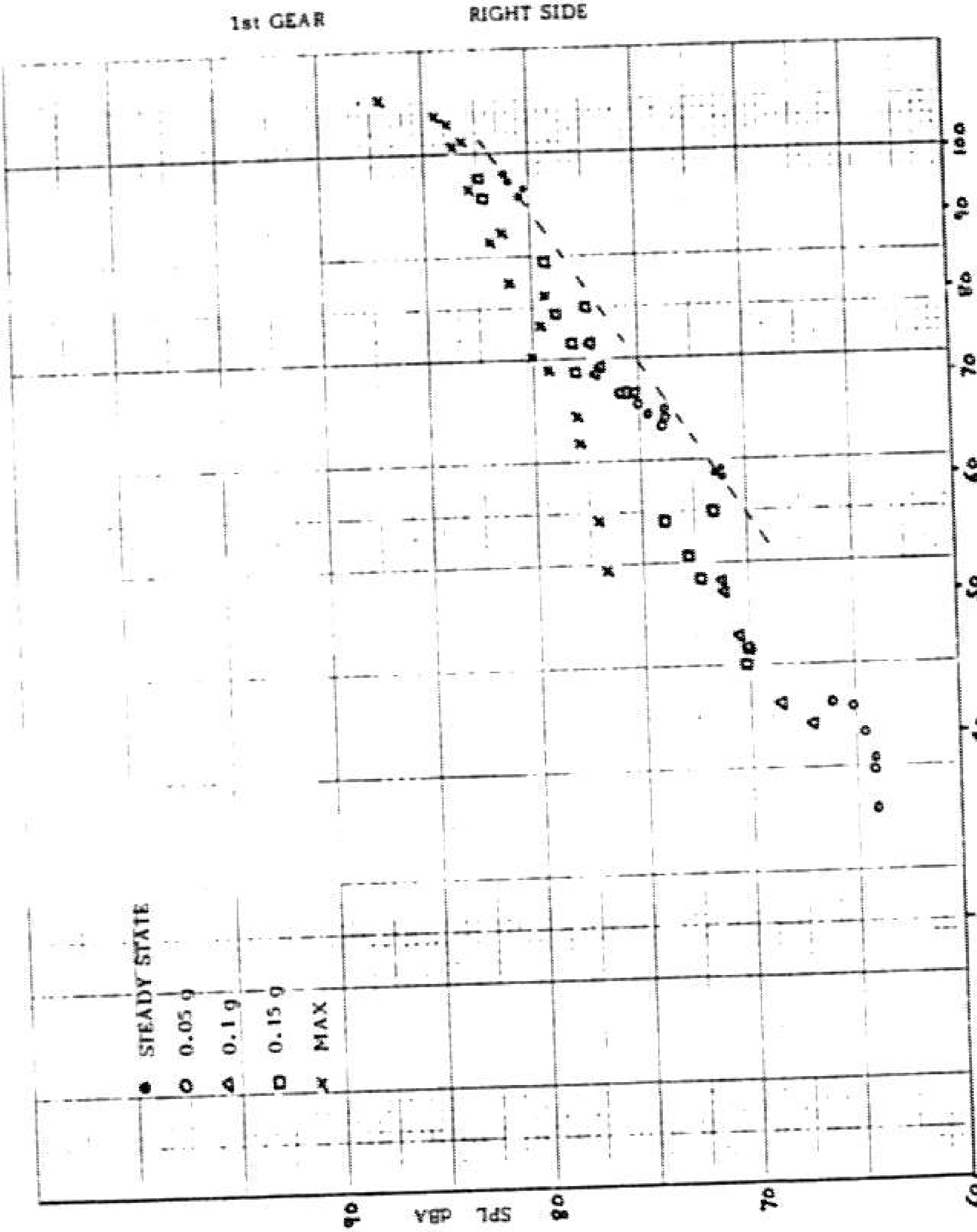


FIGURE 2-4. SAAB - ENGINE SPEED V SPL OPPOSITE MICS 1, 2 AND 3 AT VARIOUS ACCELERATION RATES

2nd GEAR LEFT SIDE

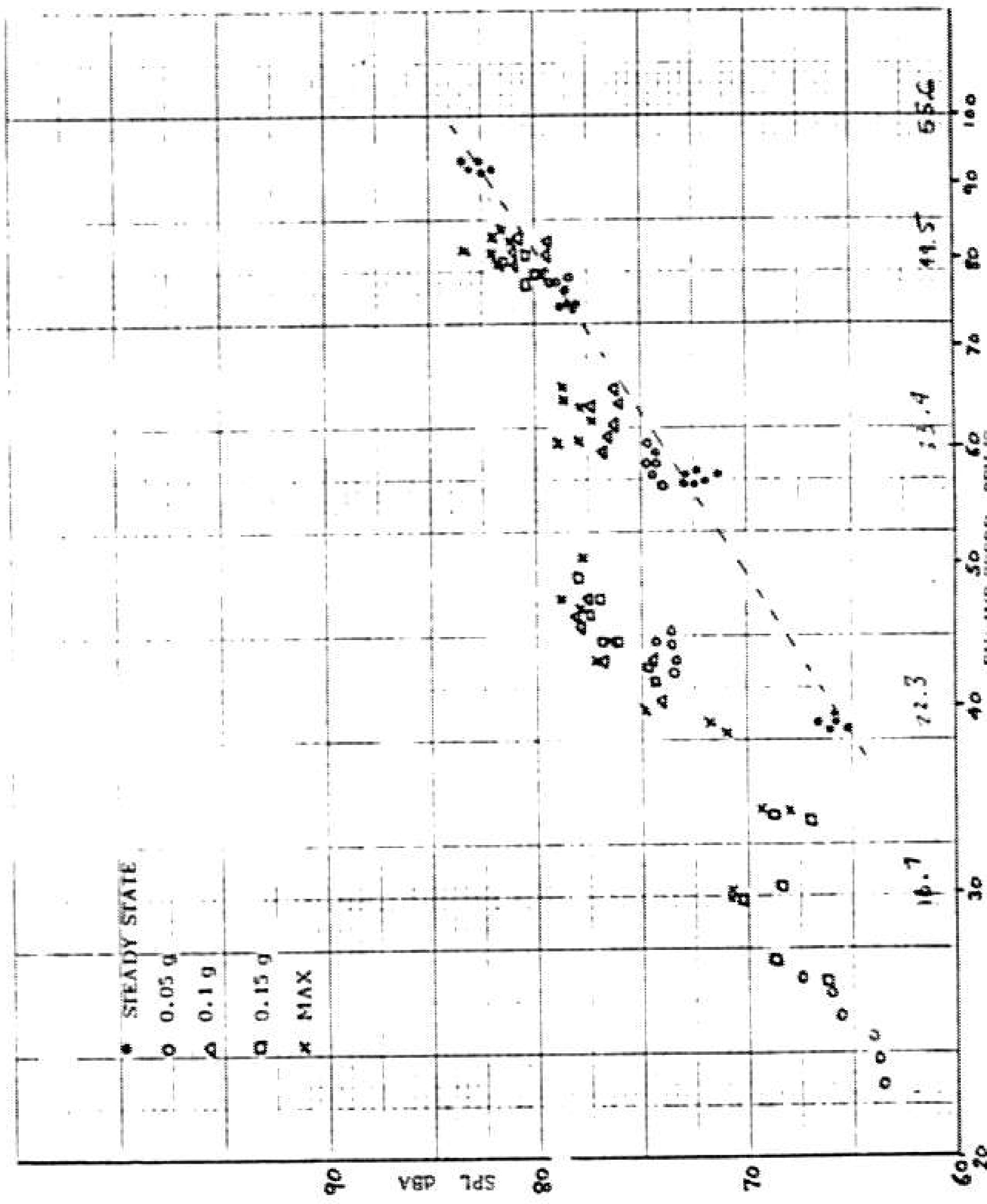


FIGURE 2-5. SAAB - ENGINE SPEED V SPL OPPOSITE MICS 1, 2 AND 3 AT VARIOUS ACCELERATION RATES

2nd GEAR RIGHT SIDE

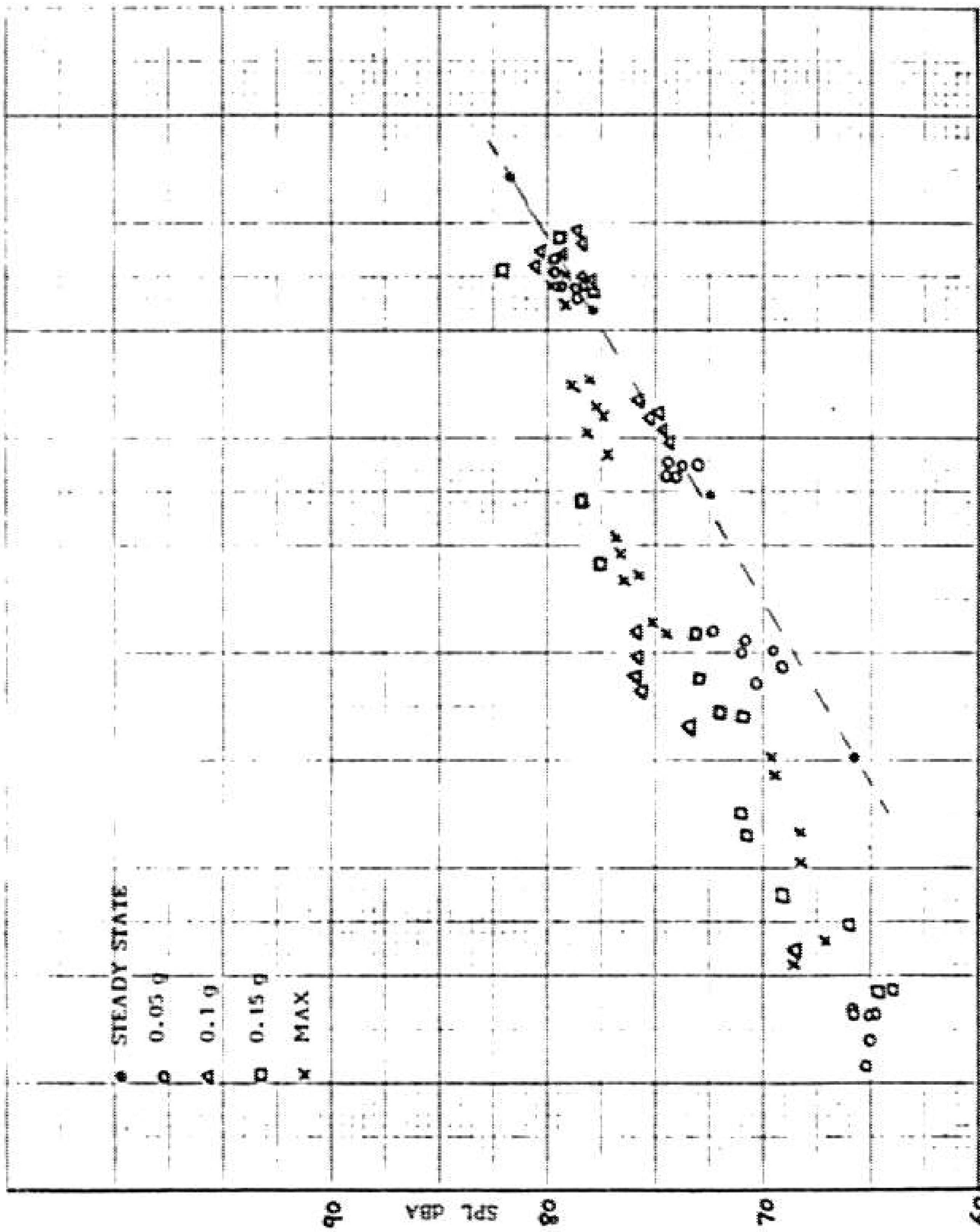


FIGURE 2-6. SAAB - ENGINE SPEED V SPL OPPOSITE MICS 1, 2 AND 3 AT VARIOUS ACCELERATION RATES

3rd GEAR LEFT SIDE

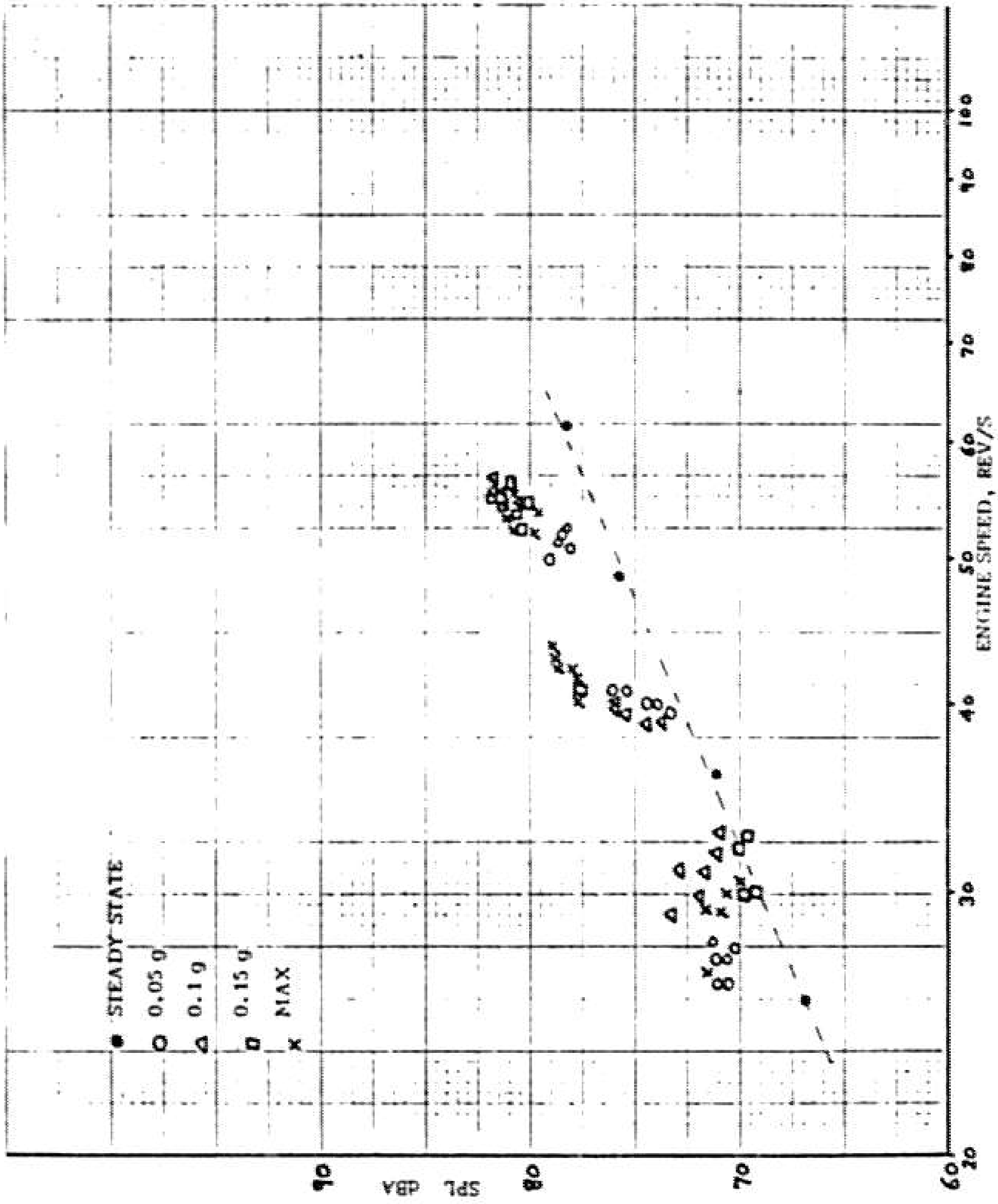


FIGURE 2-7. SAAB - ENGINE SPEED V SPL OPPOSITE MICS 1, 2 AND 3 AT VARIOUS ACCELERATION RATES

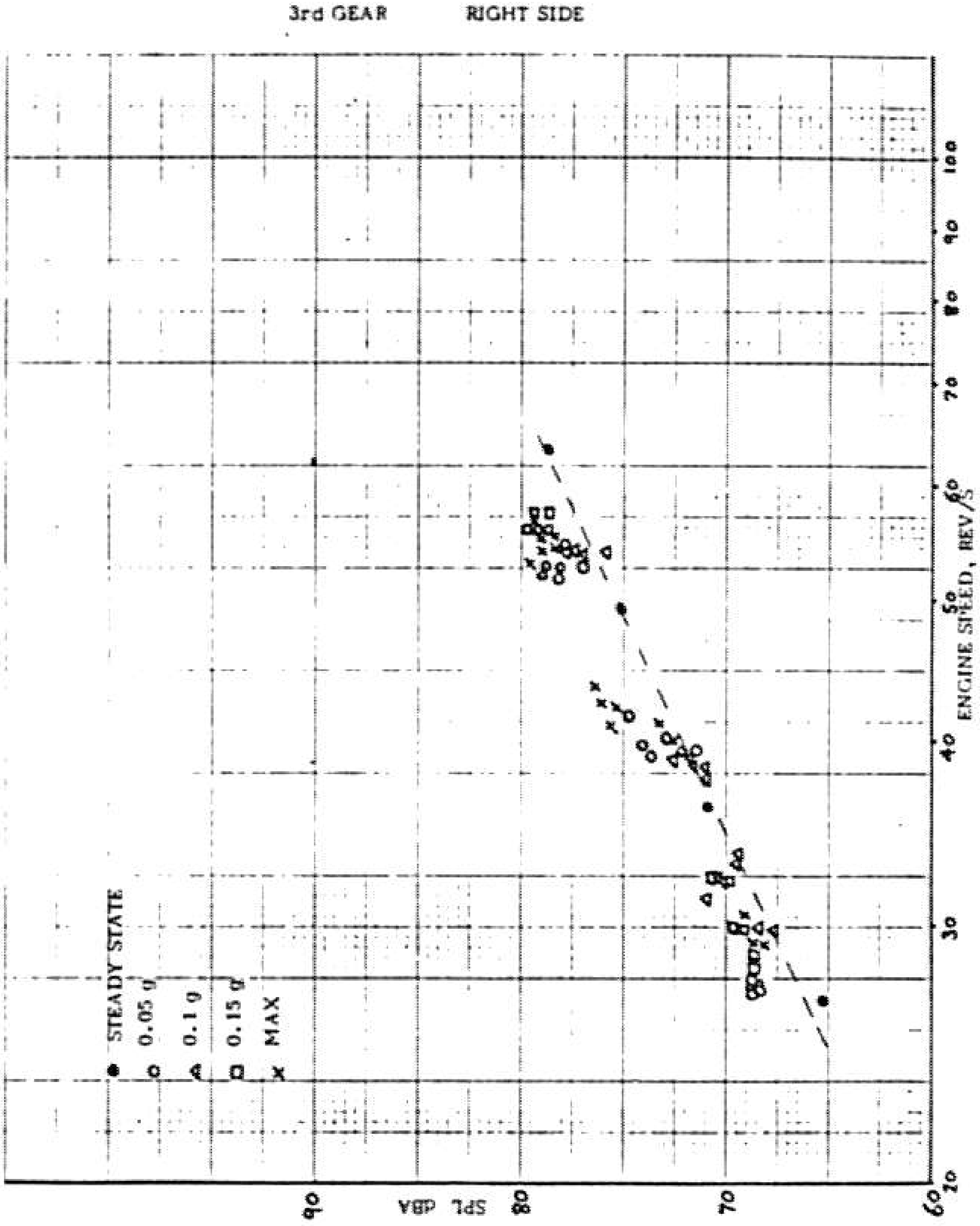


FIGURE 2-8. SAAB - ENGINE SPEED V SPL OPPOSITE MICS 1, 2 AND 3 AT VARIOUS ACCELERATION RATES

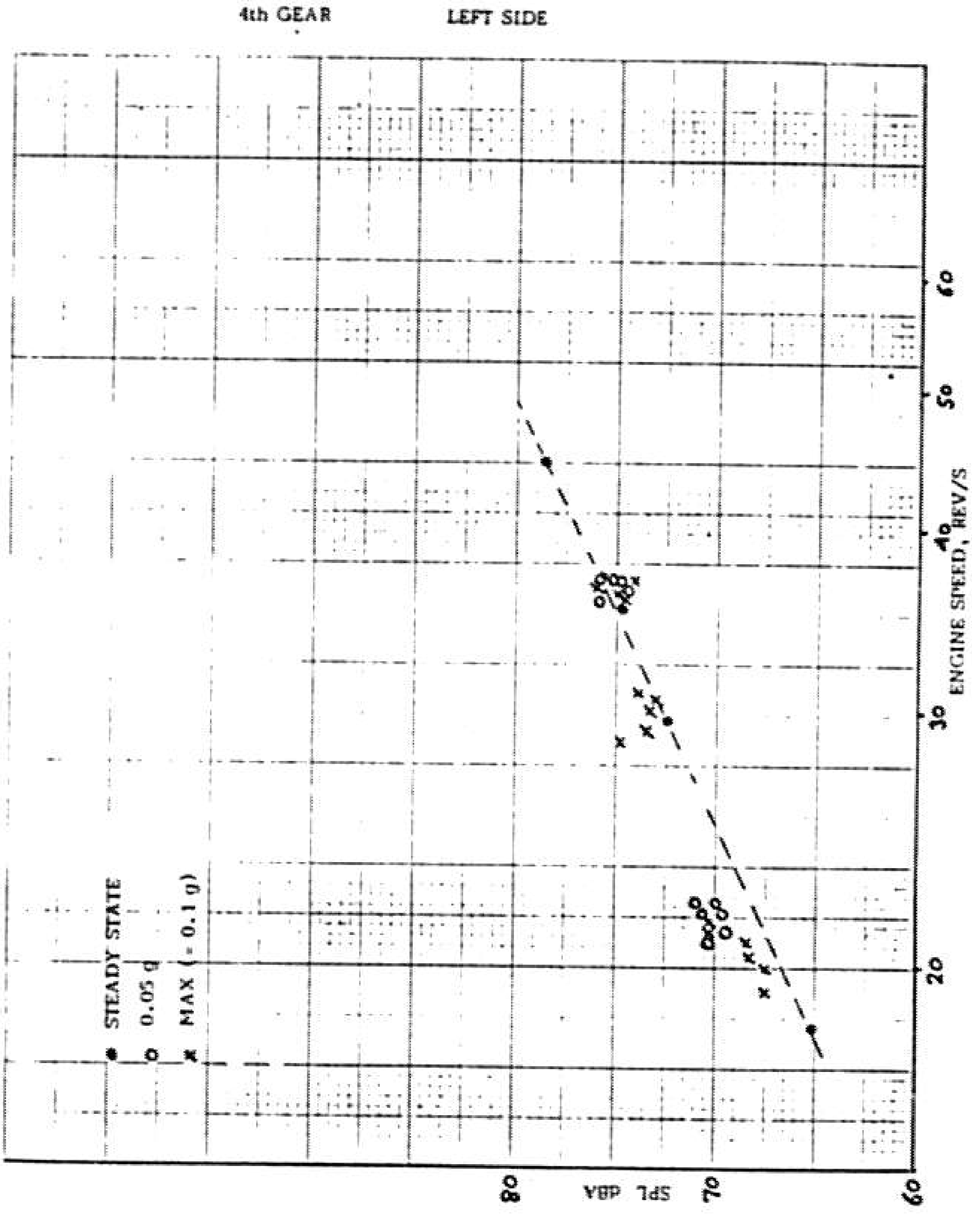


FIGURE 2-9. SAAB - ENGINE SPEED V SPL OPPOSITE MICS 1, 2 AND 3 AT VARIOUS ACCELERATION RATES

4th GEAR RIGHT SIDE

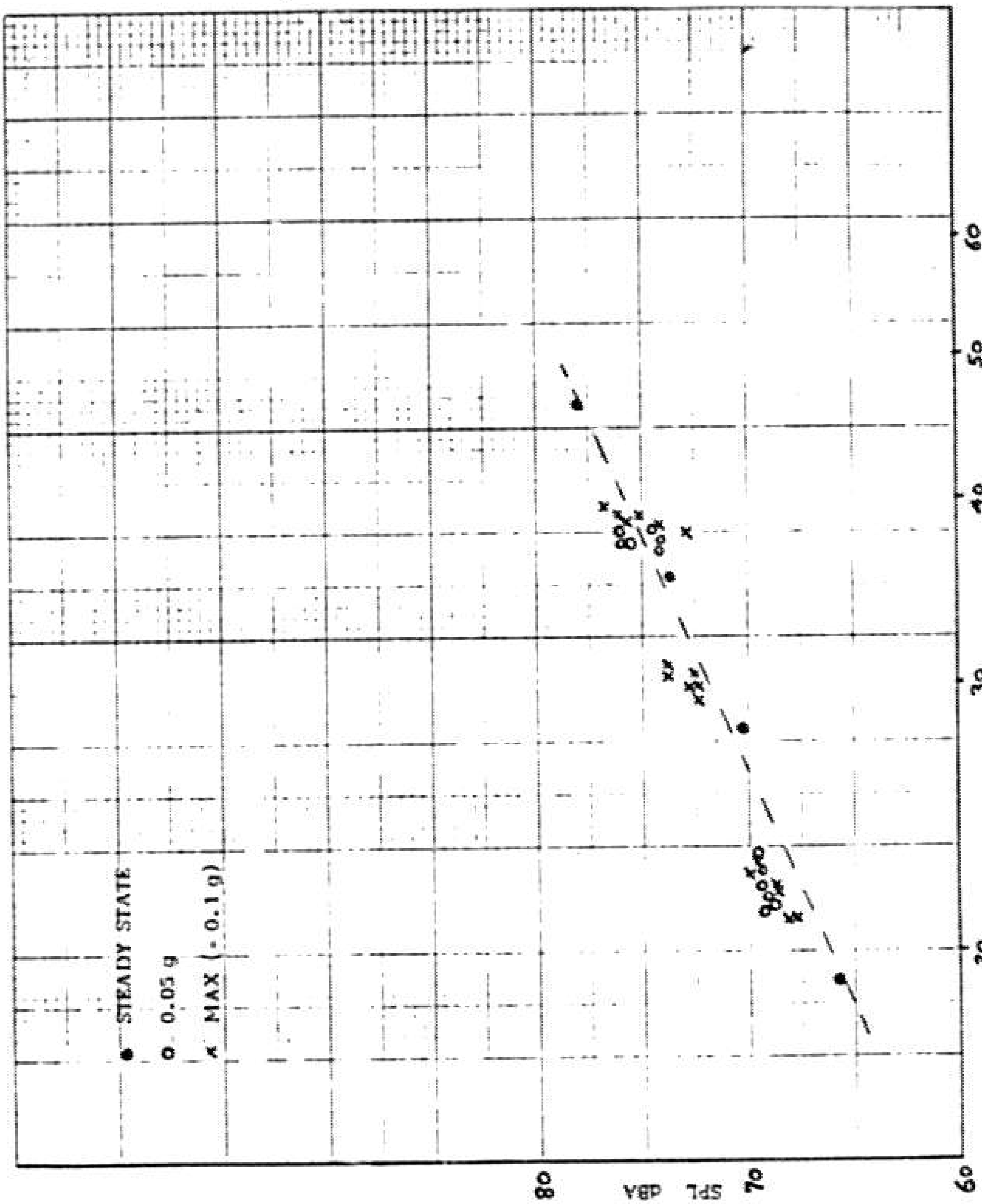


FIGURE 2-10. SAAB - ENGINE SPEED V SPL OPPOSITE MICS 1, 2 AND 3 AT VARIOUS ACCELERATION RATES

2nd GEAR LEFT SIDE 0.1 g ACCEL.

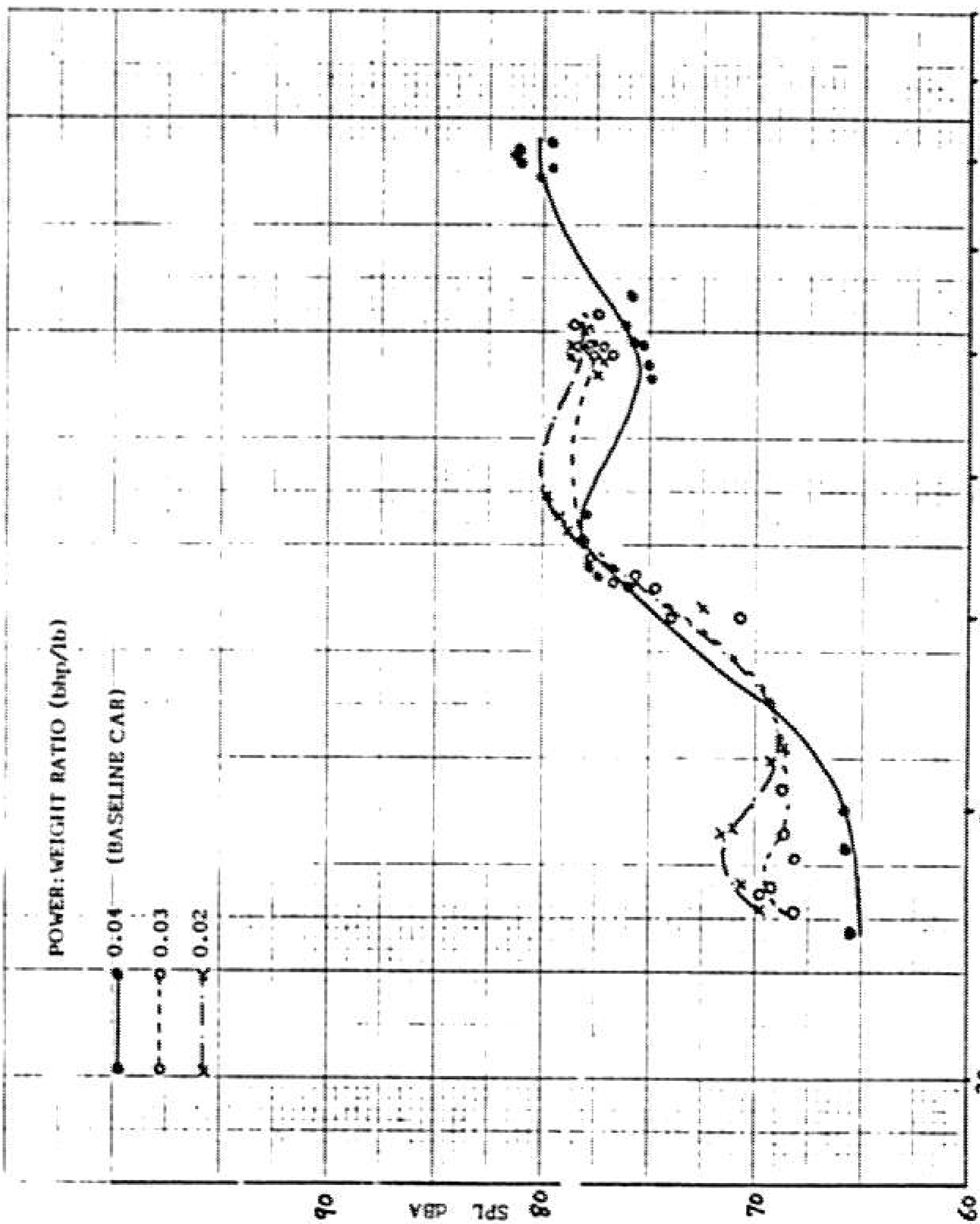
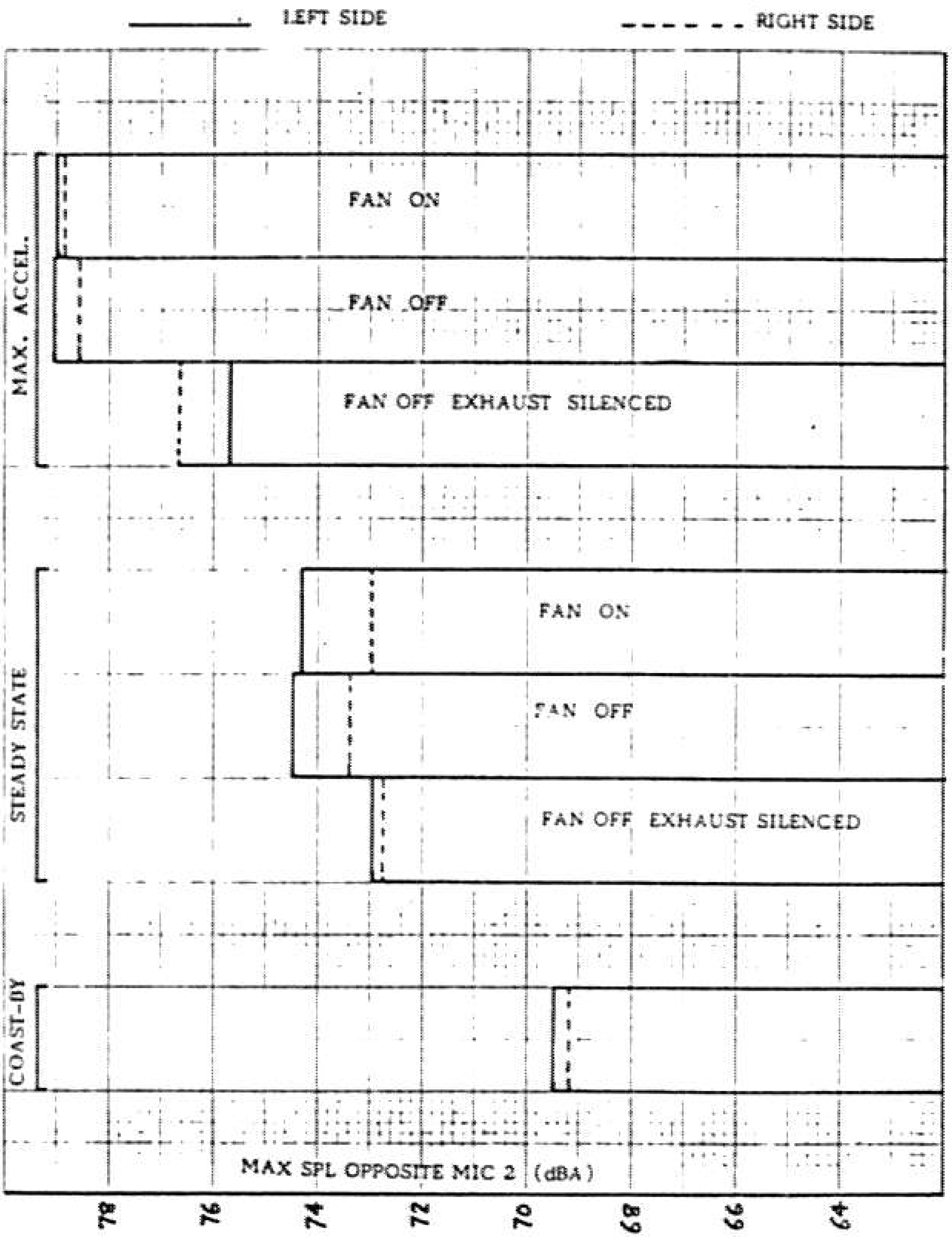


FIGURE 2-11. SAAB - ENGINE SPEED V SPL OPPOSITE MICS 1, 2 AND 3 AT VARIOUS ACCELERATION RATES

ENTRY SPEED = 30 MILE/H
GEAR = 2nd



FIGUER 2-12. SAAB - NOISE SOURCE TESTS (DRIVE-BY)

ENTRY SPEED : 30 MILE/H

2nd GEAR

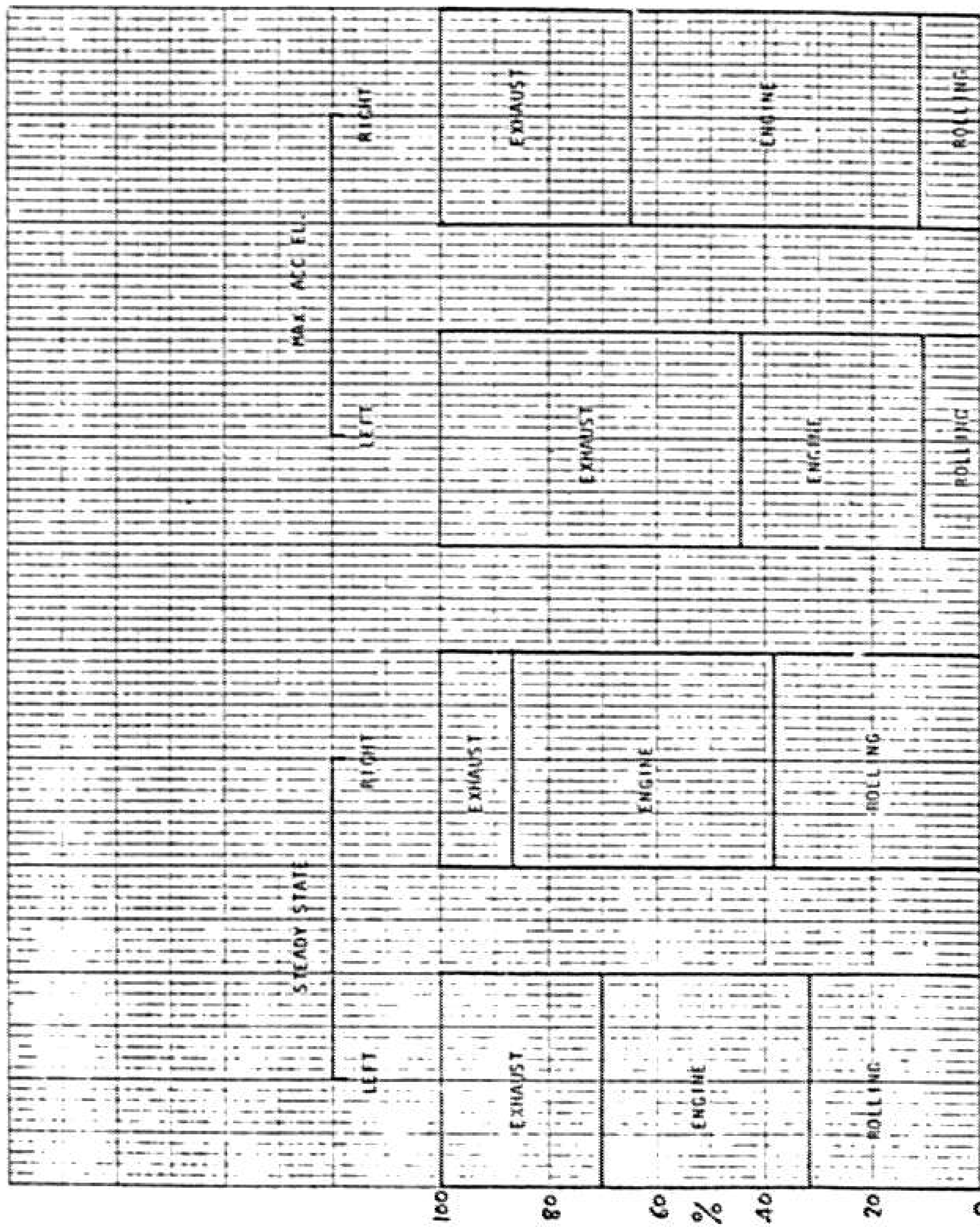


FIGURE 2-13. SAAB - NOISE SOURCE BREAKDOWN (ON DRIVE-BY BASIS)

AS FUNCTION OF CONSTANT ROLLING NOISE
ENTRY SPEED : 30 MILE/H
2nd GEAR

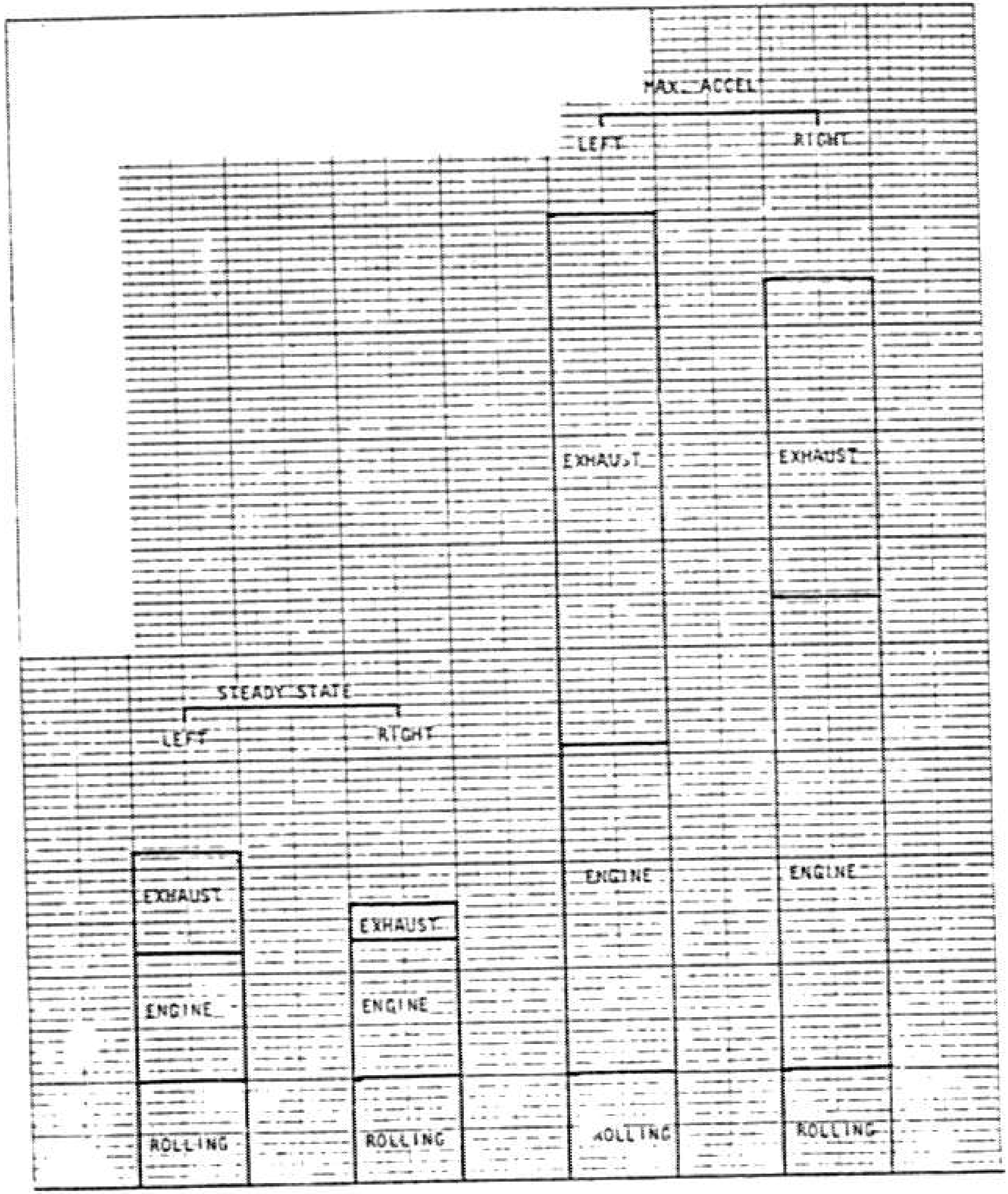


FIGURE 2-14. SAAB - NOISE SOURCE BREAKDOWN (ON DRIVE-BY BASIS)

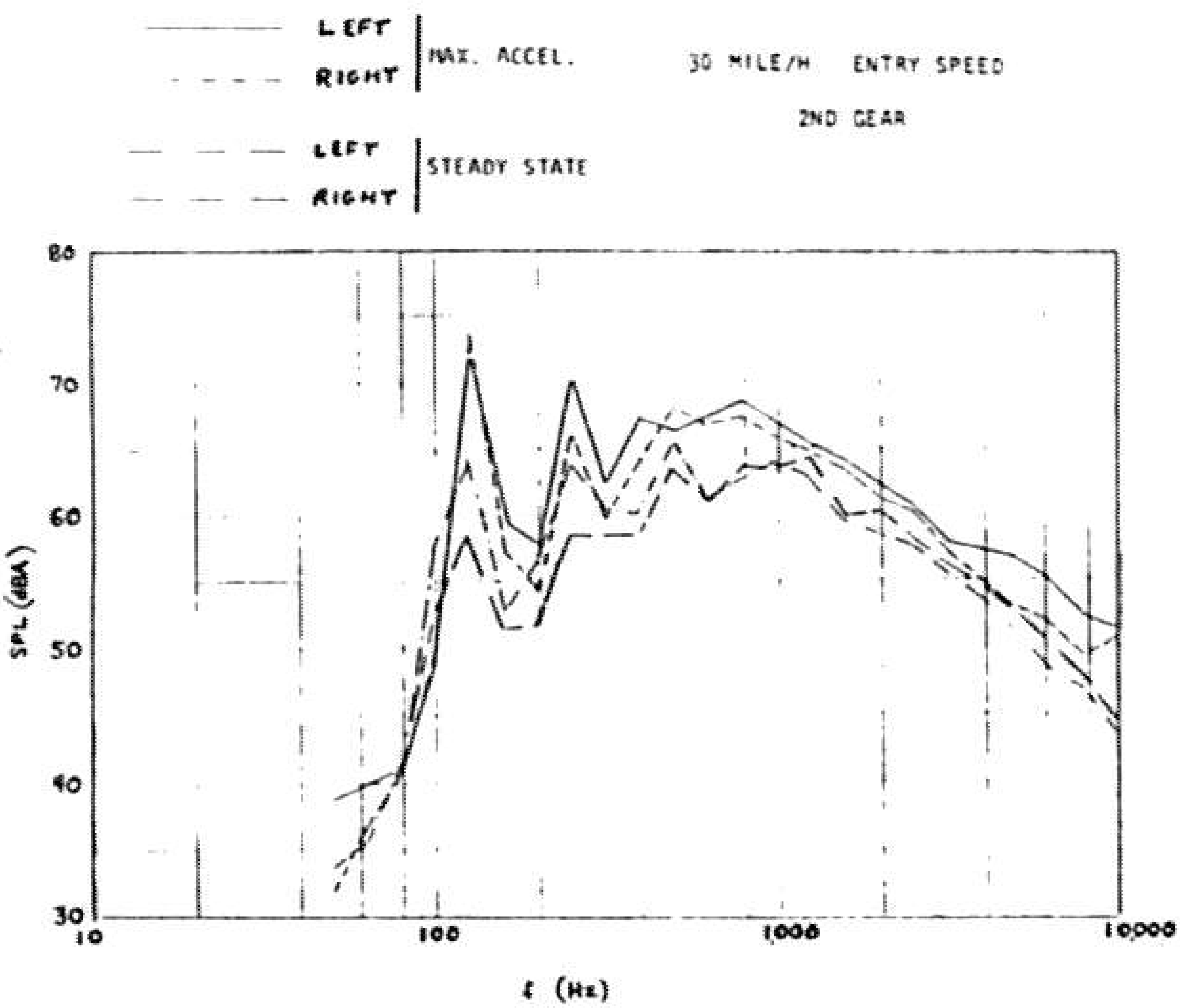


FIGURE 2-15. SAAB - MAXIMUM DRIVE-BY SPECTRA AT MIC.2

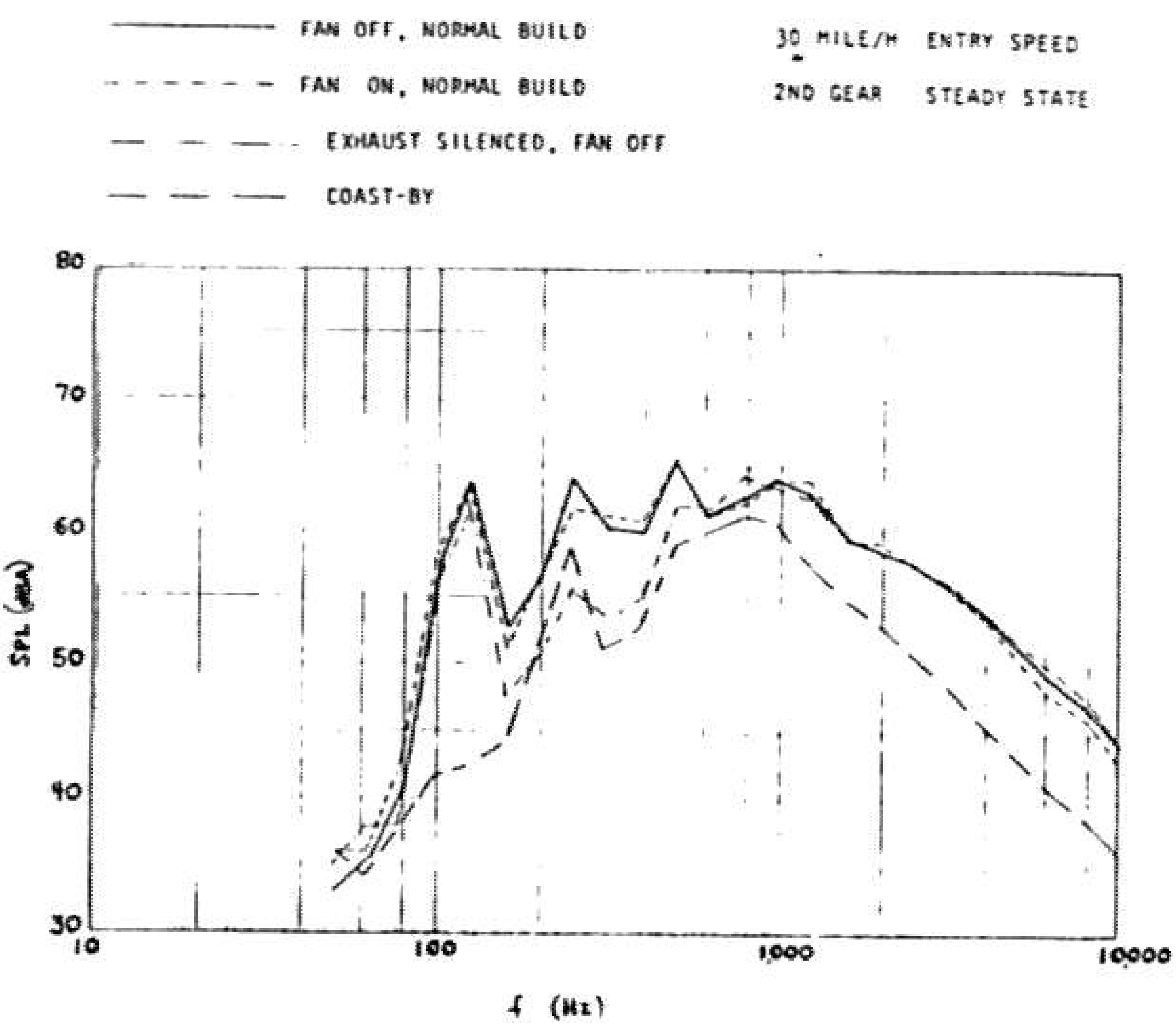


FIGURE 2-16. SAAB - NOISE SOURCE TESTS DRIVE-BY SPECTRA (MAXIMA AT MIC. 2)

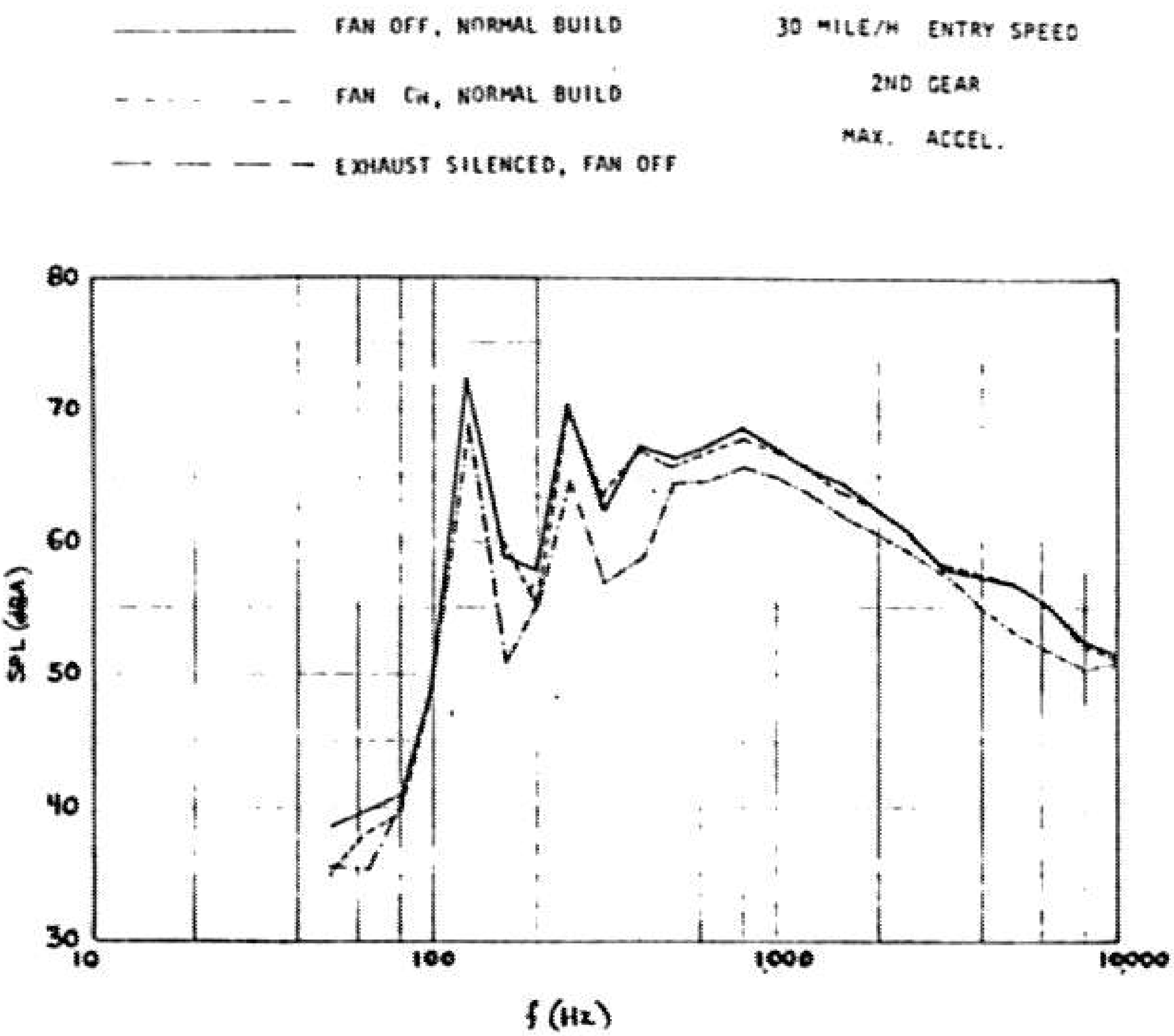


FIGURE 2-17. SAAB - NOISE SOURCE TESTS DRIVE-BY SPECTRA (MAXIMA AT MIC.2)

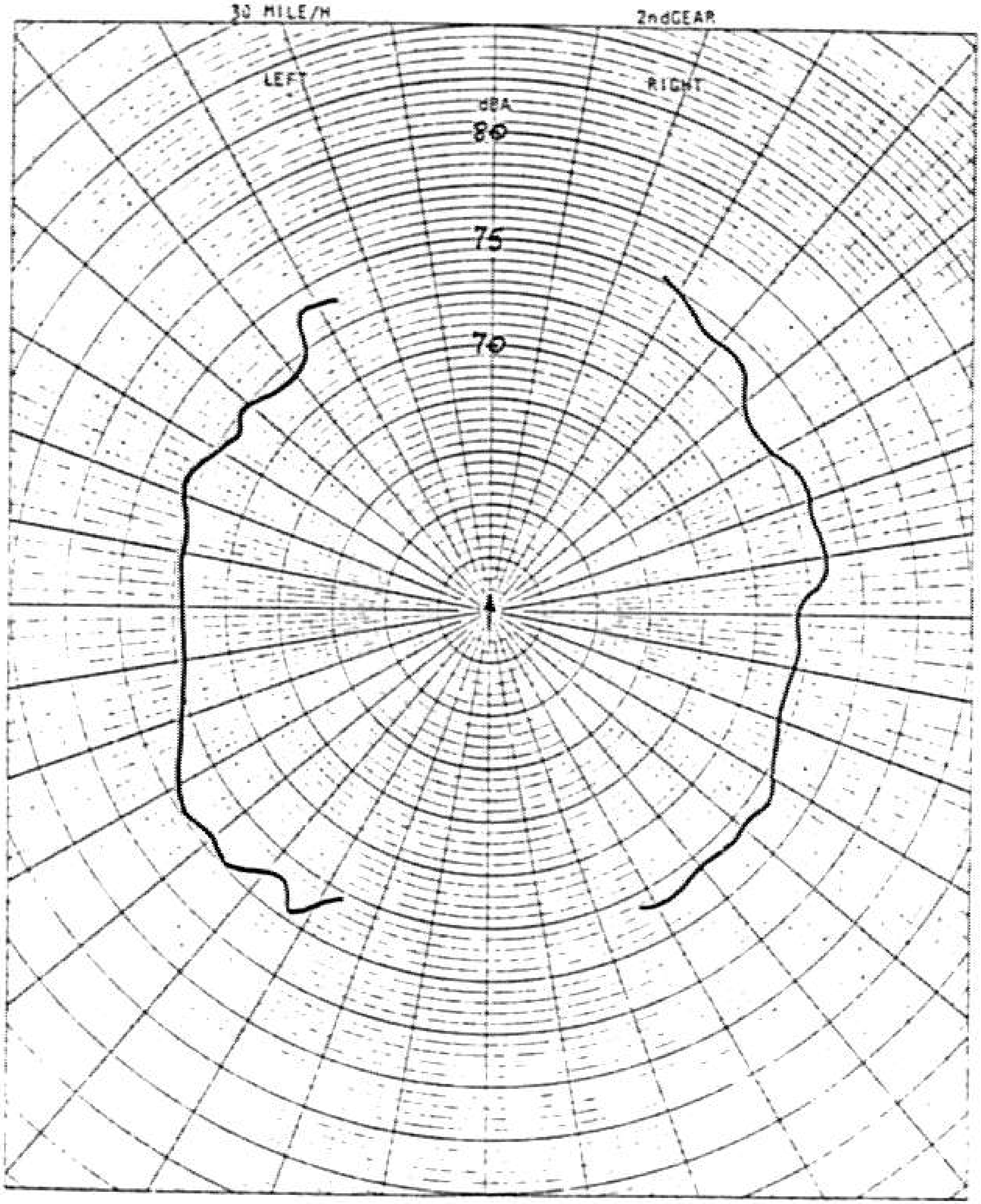


FIGURE 2-18. SAAB - POLAR NOISE DISTRIBUTION FROM DRIVE-BY TEST SPL NORMALIZED TO 7.5m

50 MILE/H 2nd GEAR

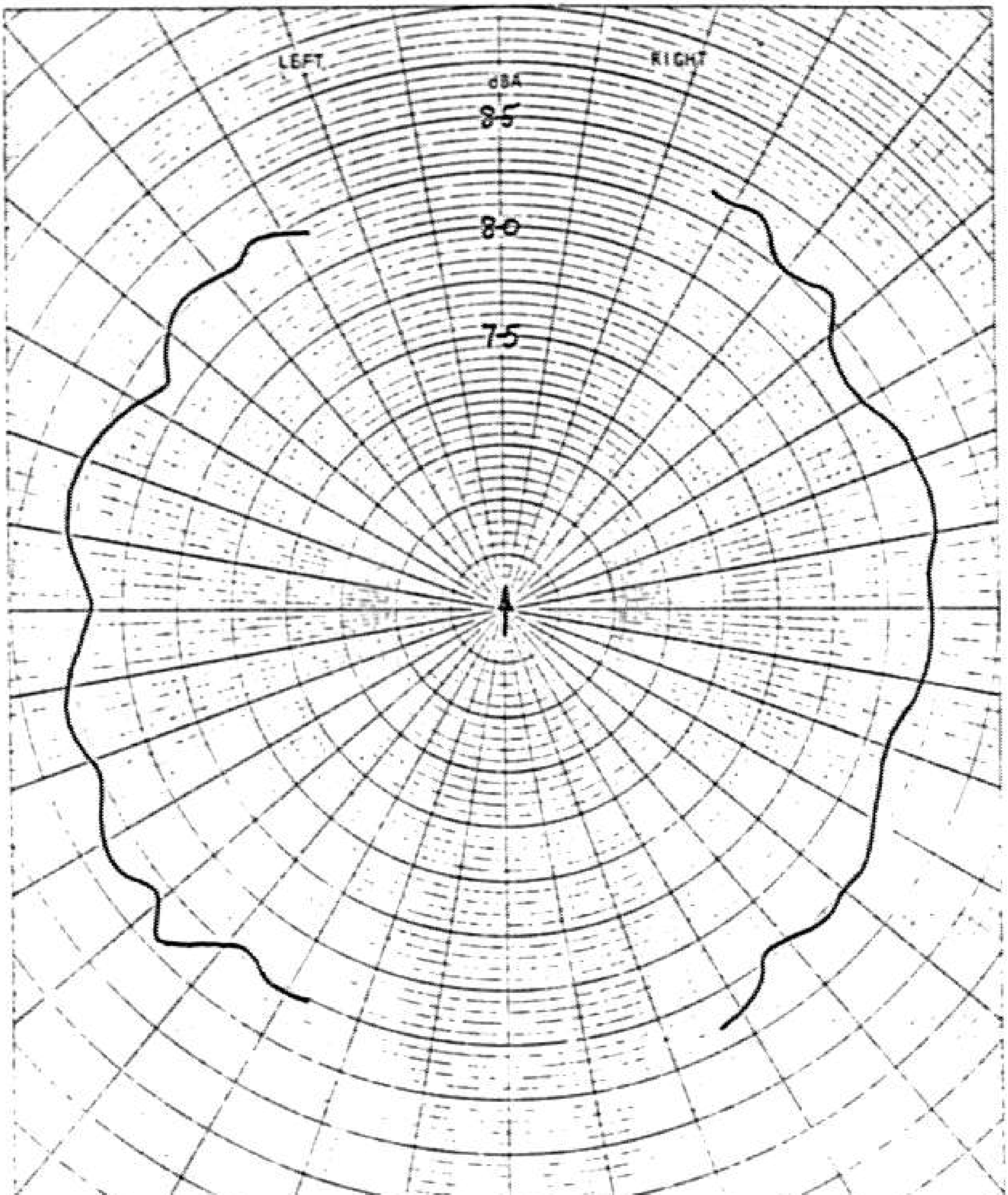


FIGURE 2-19. SAAB - POLAR NOISE DISTRIBUTION FROM DRIVE-BY TEST
SPL NORMALIZED TO 7.5 m

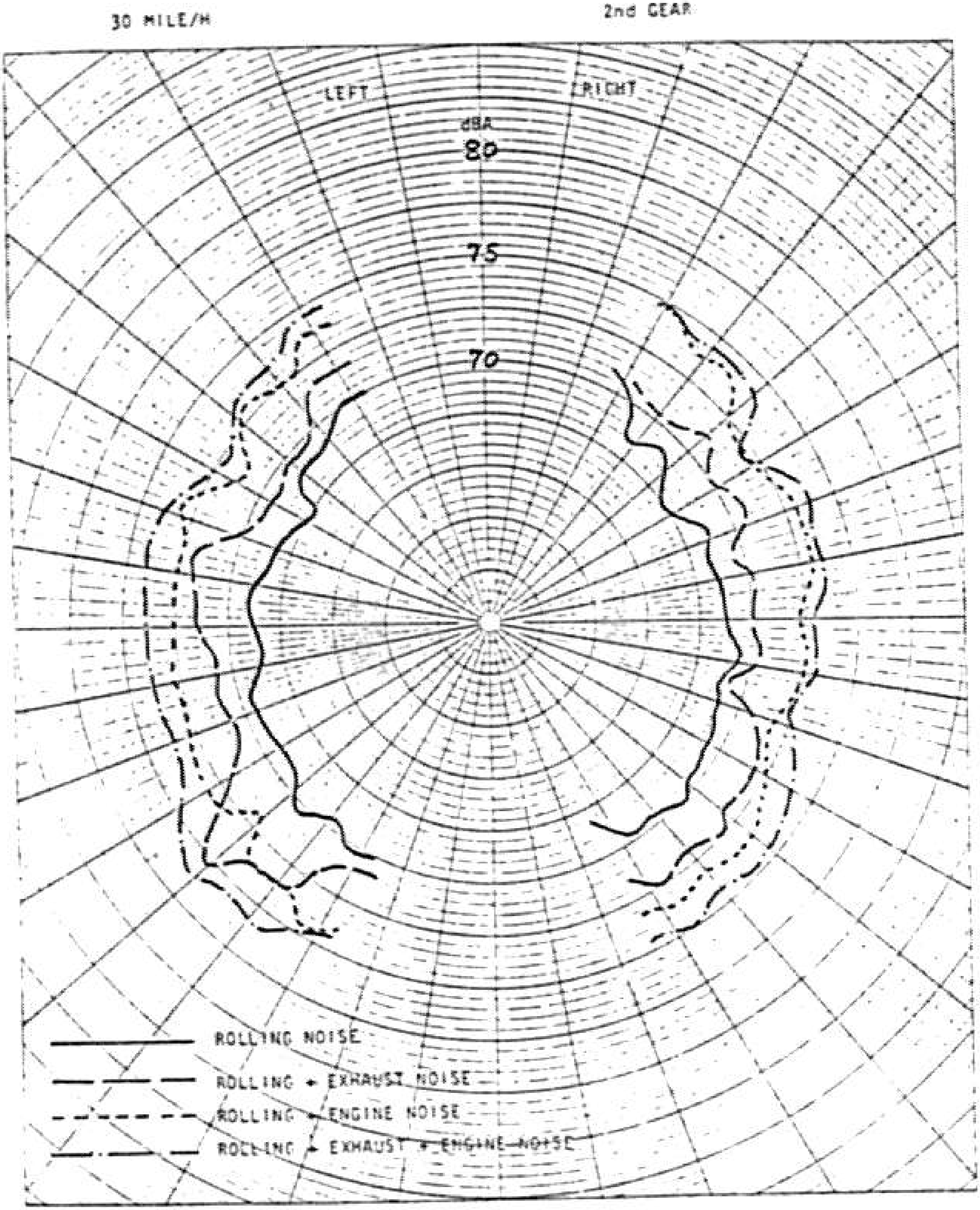


FIGURE 2-20. SAAB - NOISE SOURCES POLAR DISTRIBUTION FROM DRIVE-BY TESTS SPL NORMALIZED TO 7.5m

LEFT SIDE

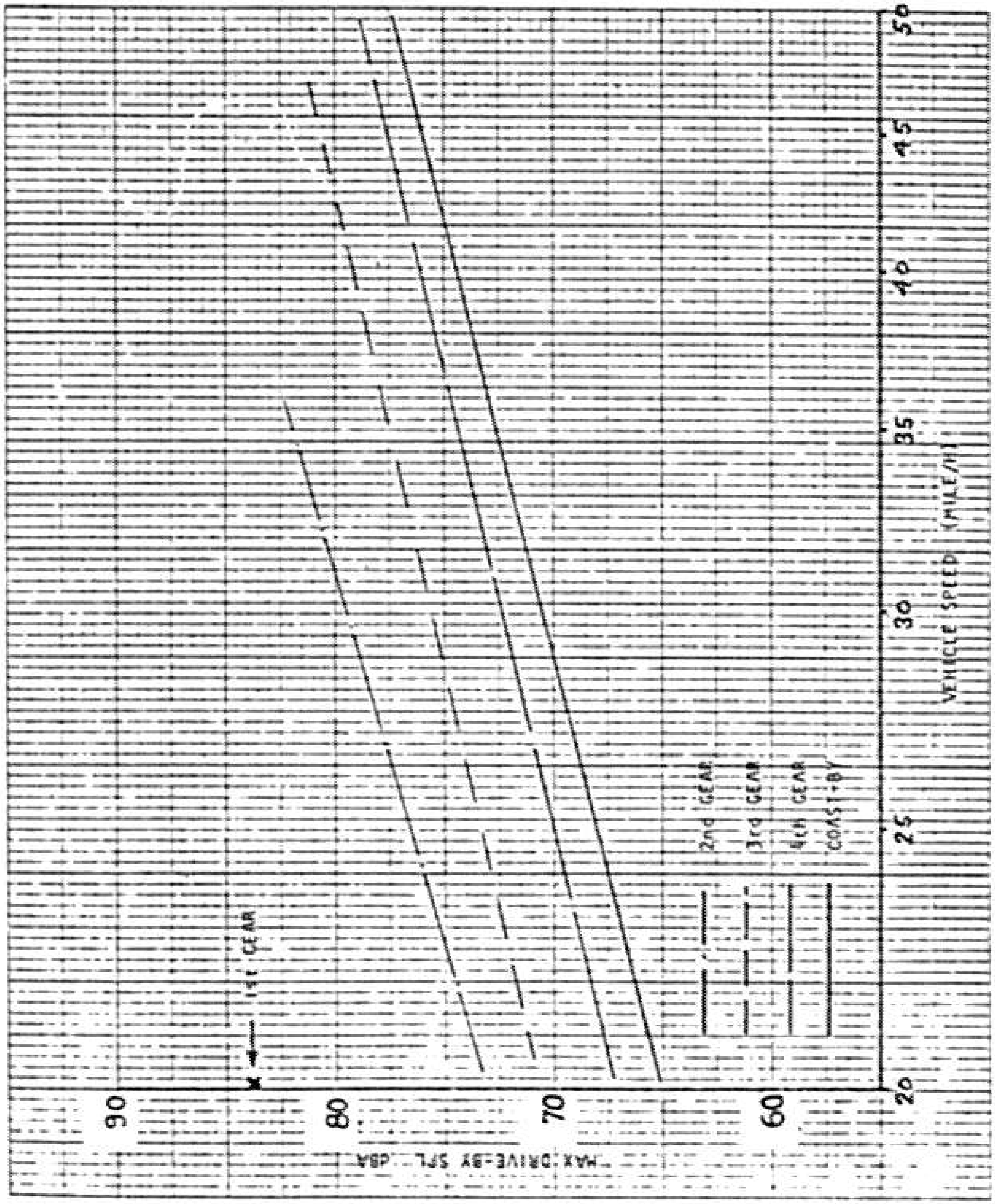


FIGURE 2-21. PEUGEOT - EFFECT OF VEHICLE SPEED AND GEAR RATIO ON MAXIMUM DRIVE-BY SPL FOR STEADY STATE TESTS (INCLUDING COAST-BY)

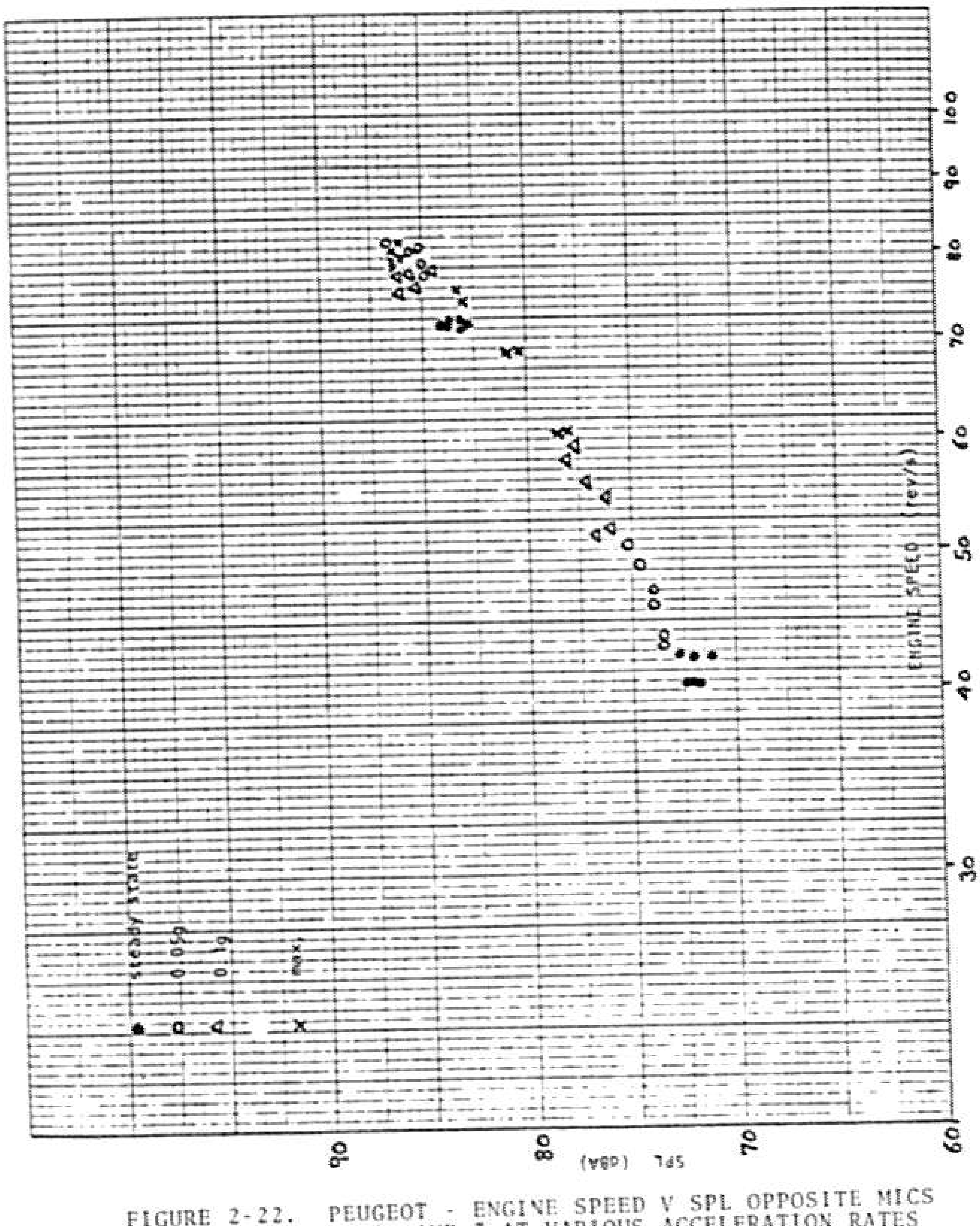


FIGURE 2-22. PEUGEOT - ENGINE SPEED V SPL OPPOSITE MICS 1, 2, AND 3 AT VARIOUS ACCELERATION RATES

1st GEAR RIGHT SIDE

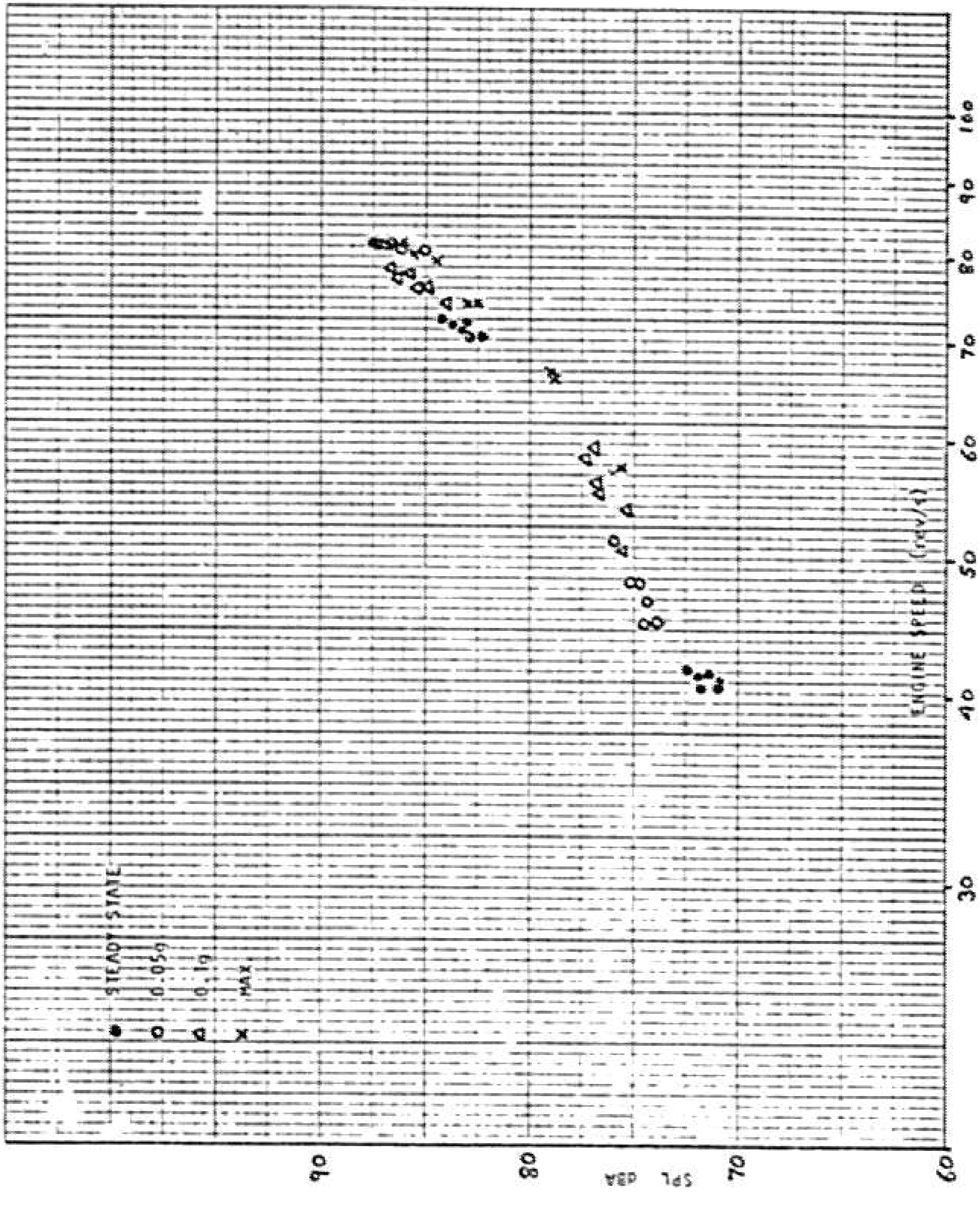


FIGURE 2-23. PEUGEOT - ENGINE SPEED V SPL OPPOSITE MICS 1, 2, AND 3 AT VARIOUS ACCELERATION RATES

2nd GEAR

LEFT SIDE

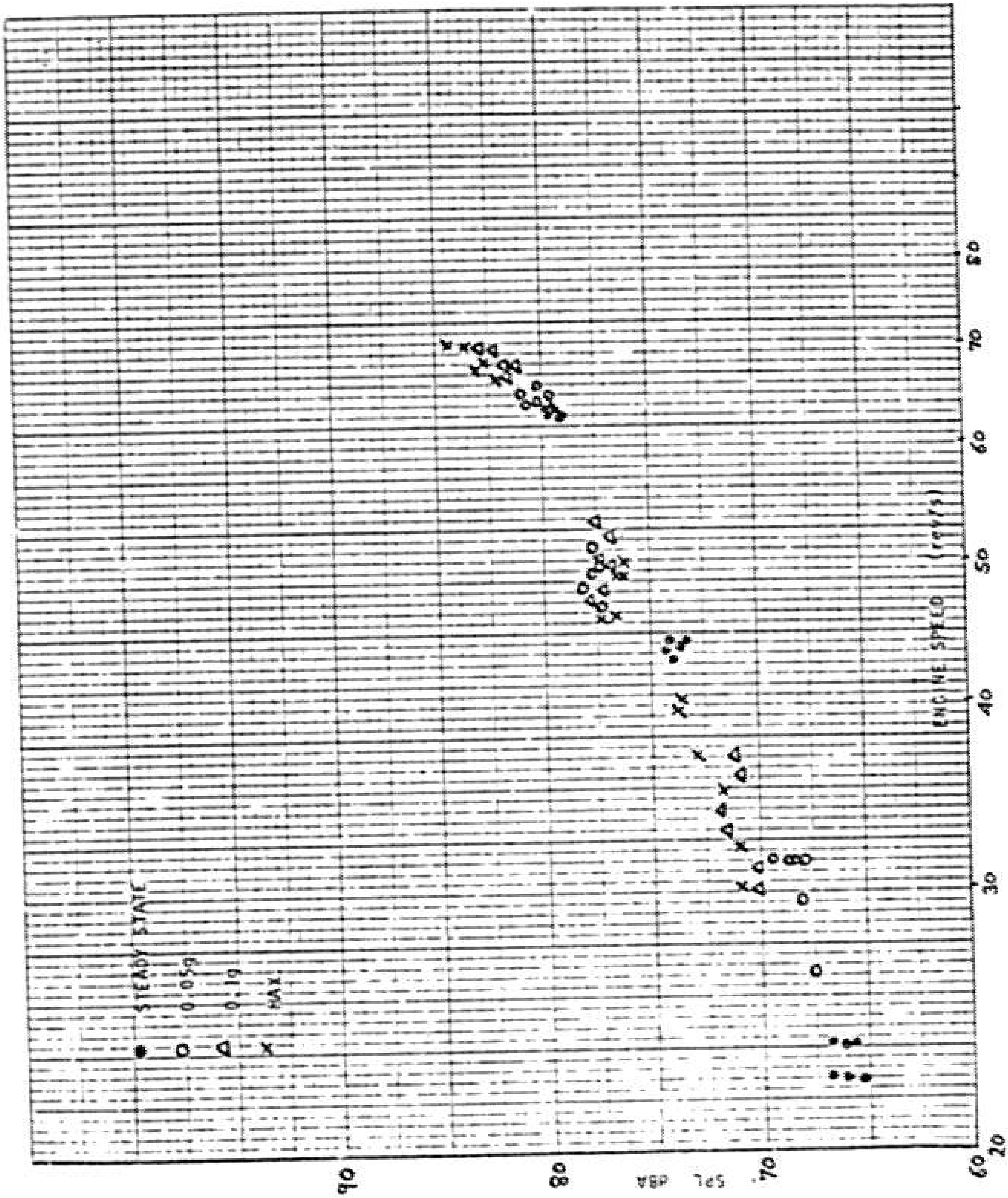


FIGURE 2-24. PEUGEOT - ENGINE SPEED V SPL OPPOSTIE MICS 1, 2. AND 3 AT VARIOUS ACCELERATION RATES

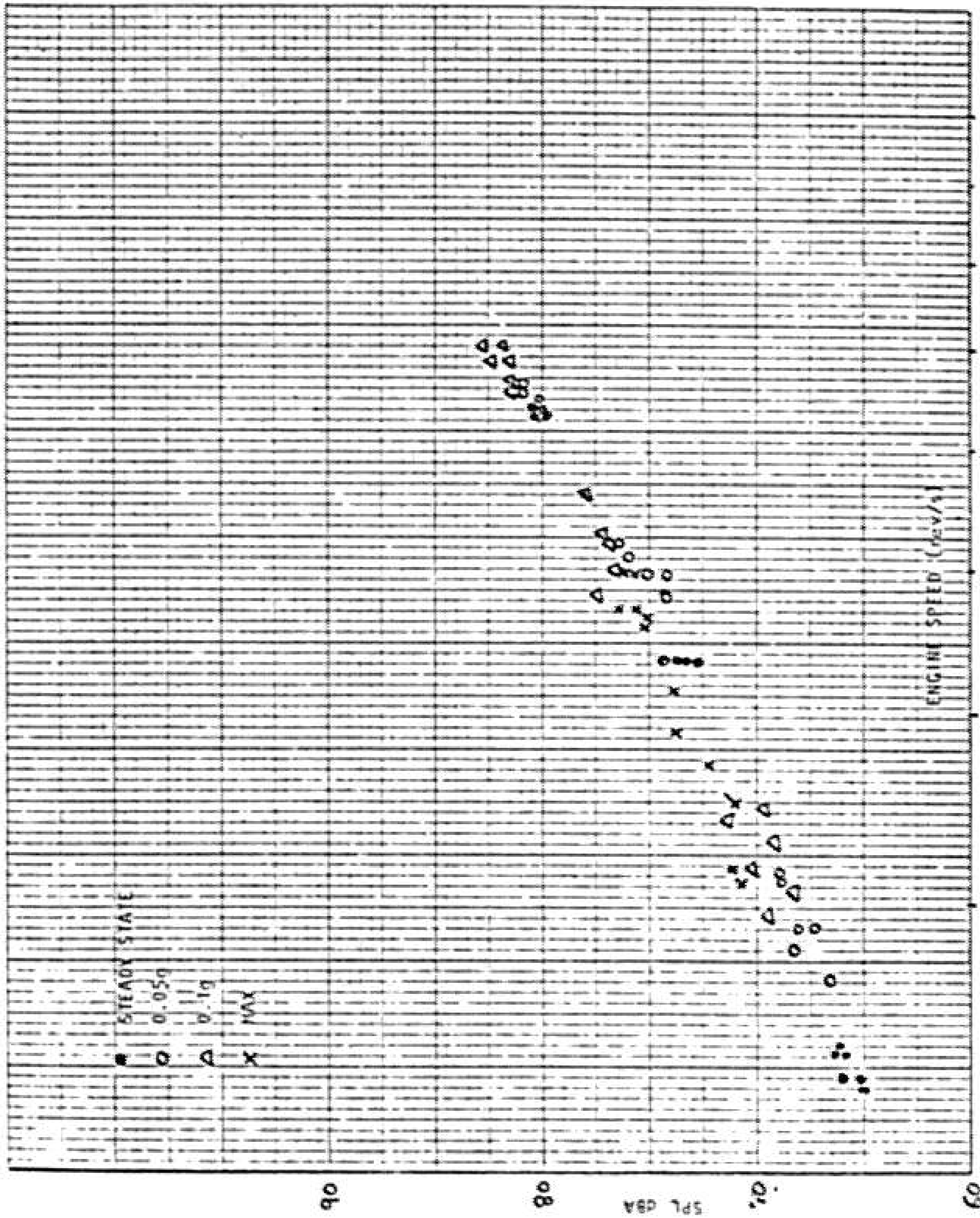


FIGURE 2-25. PEUGEOT - ENGINE SPEED V SPL OPPOSITE MICS 1, 2, AND 3 AT VARIOUS ACCELERATION RATES

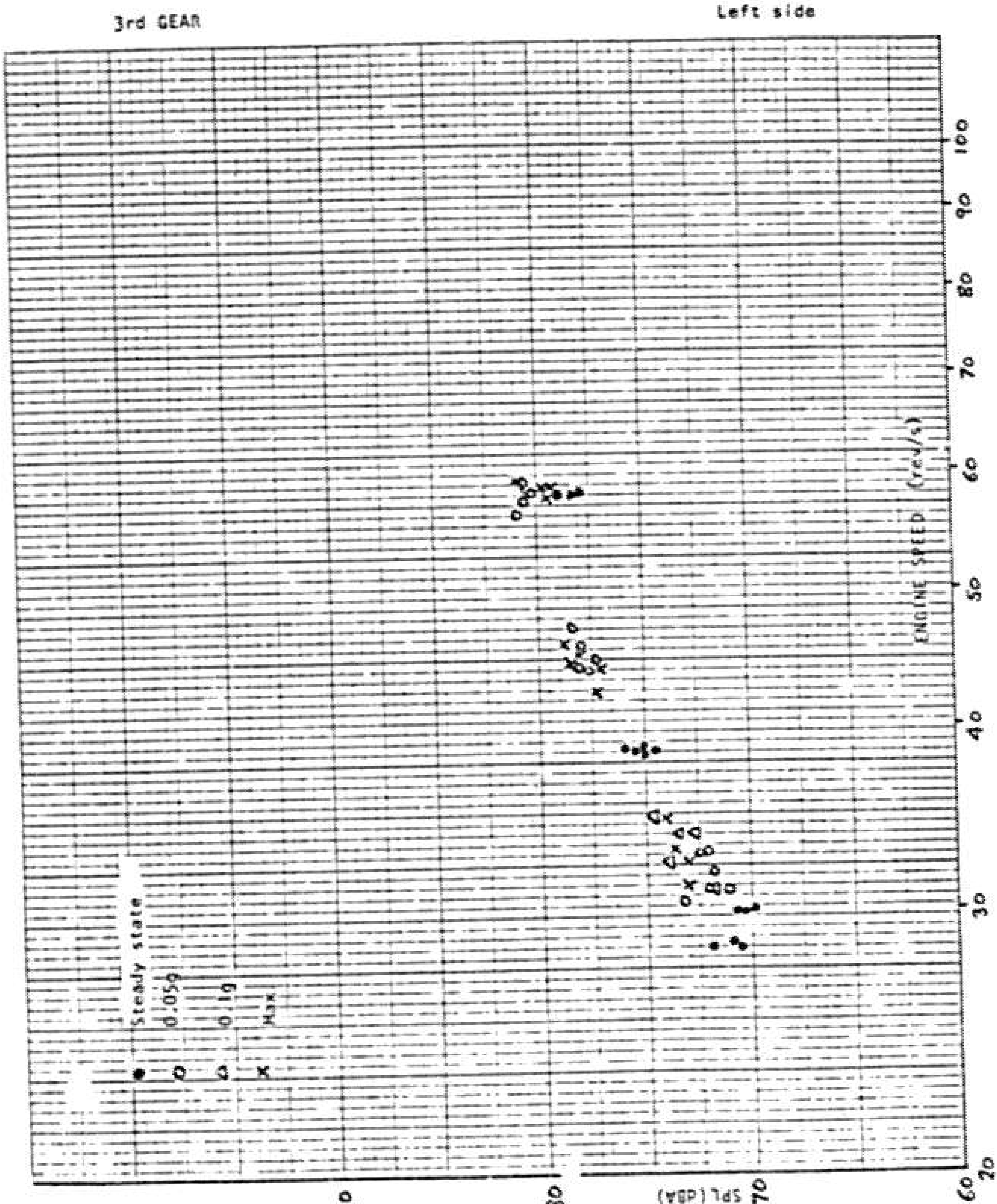


FIGURE 2-26. PEUGEOT - ENGINE SPEED V SPL OPPOSITE MICS 1, 2, AND 3 AT VARIOUS ACCELERATION RATES

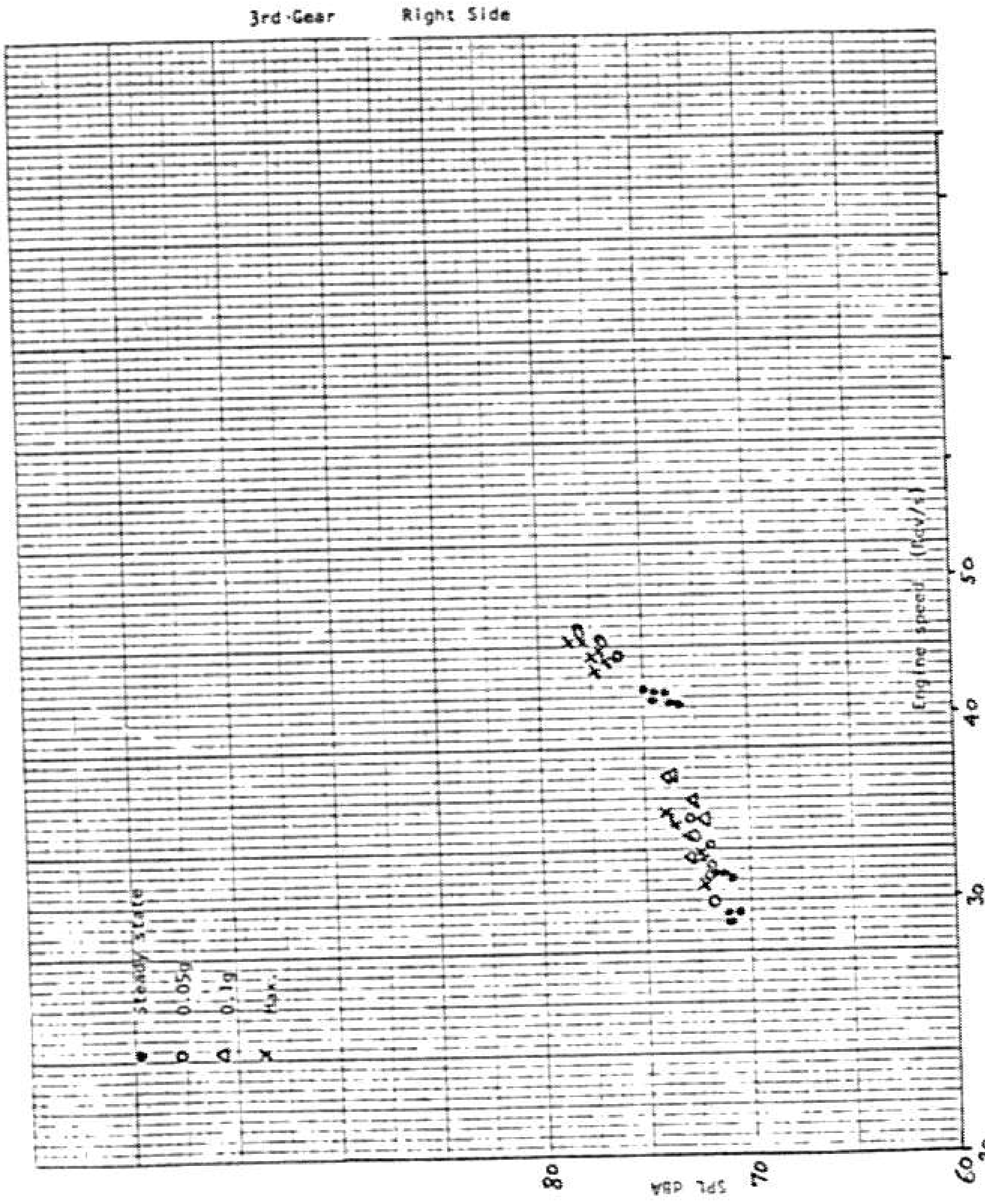


FIGURE 2-27. PEUGEOT - ENGINE SPEED V SPL OPPOSITE MICS 1, 2, AND 3 AT VARIOUS ACCELERATION RATES

4th Gear. Left side

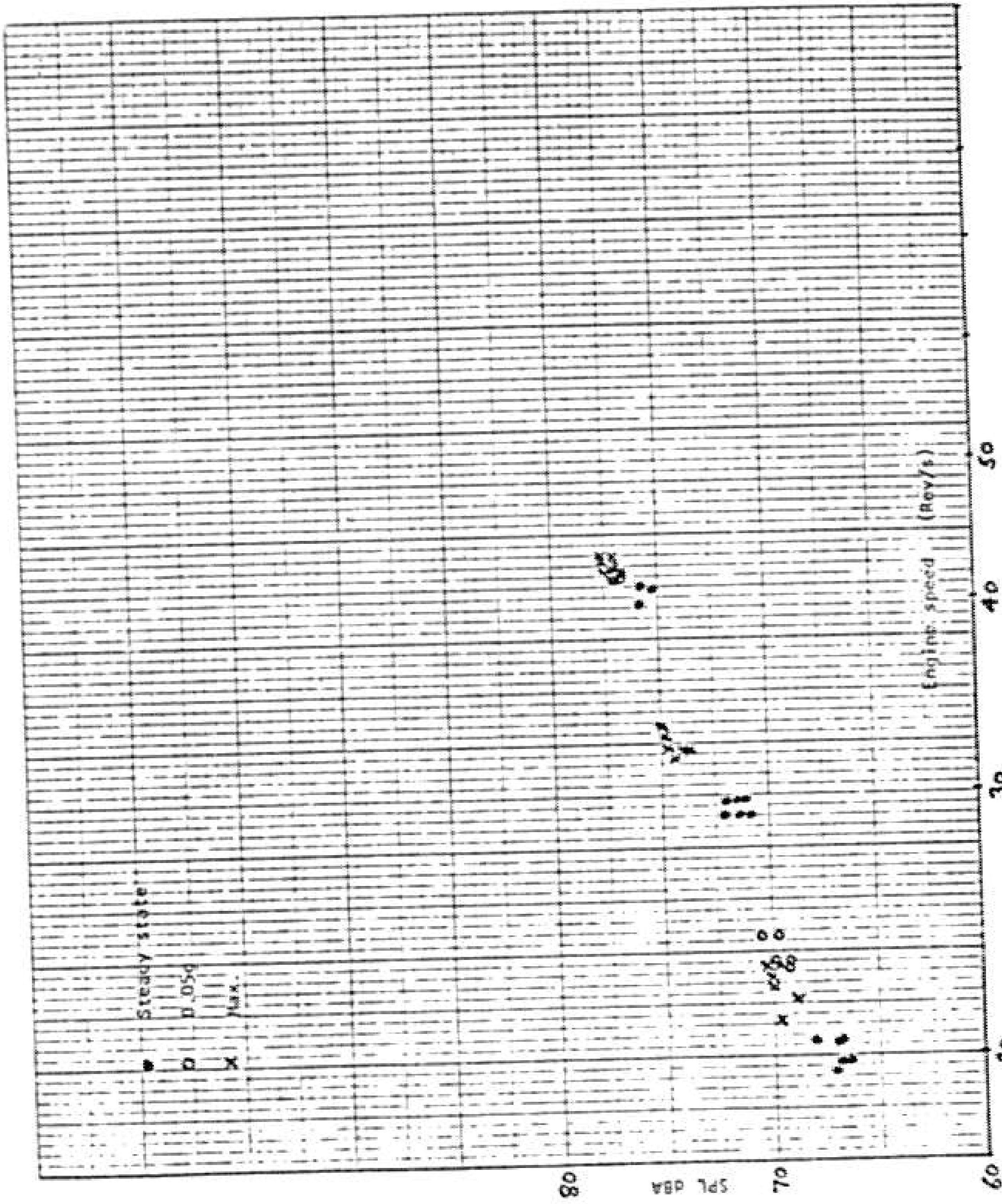


FIGURE 2-28. PEUGEOT - ENGINE SPEED V SPL OPPOSITE MICS 1, 2, AND 3 AT VARIOUS ACCELERATION RATES

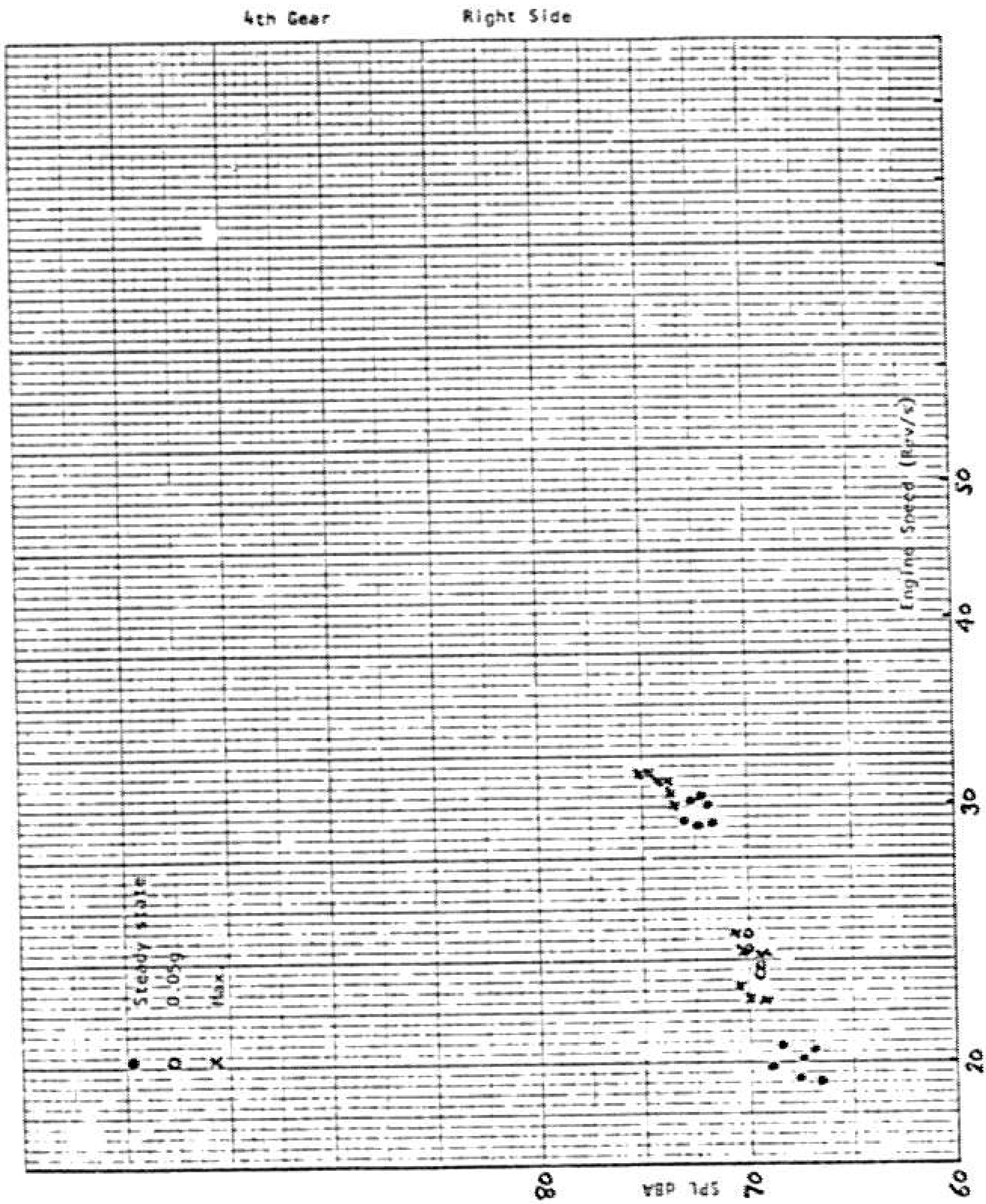


FIGURE 2-29. PEUGEOT - ENGINE SPEED V SPL OPPOSITE MICS 1, 2, AND 3 AT VARIOUS ACCELERATION RATES

ENTRY SPEED : 30 mph   2ND GEAR

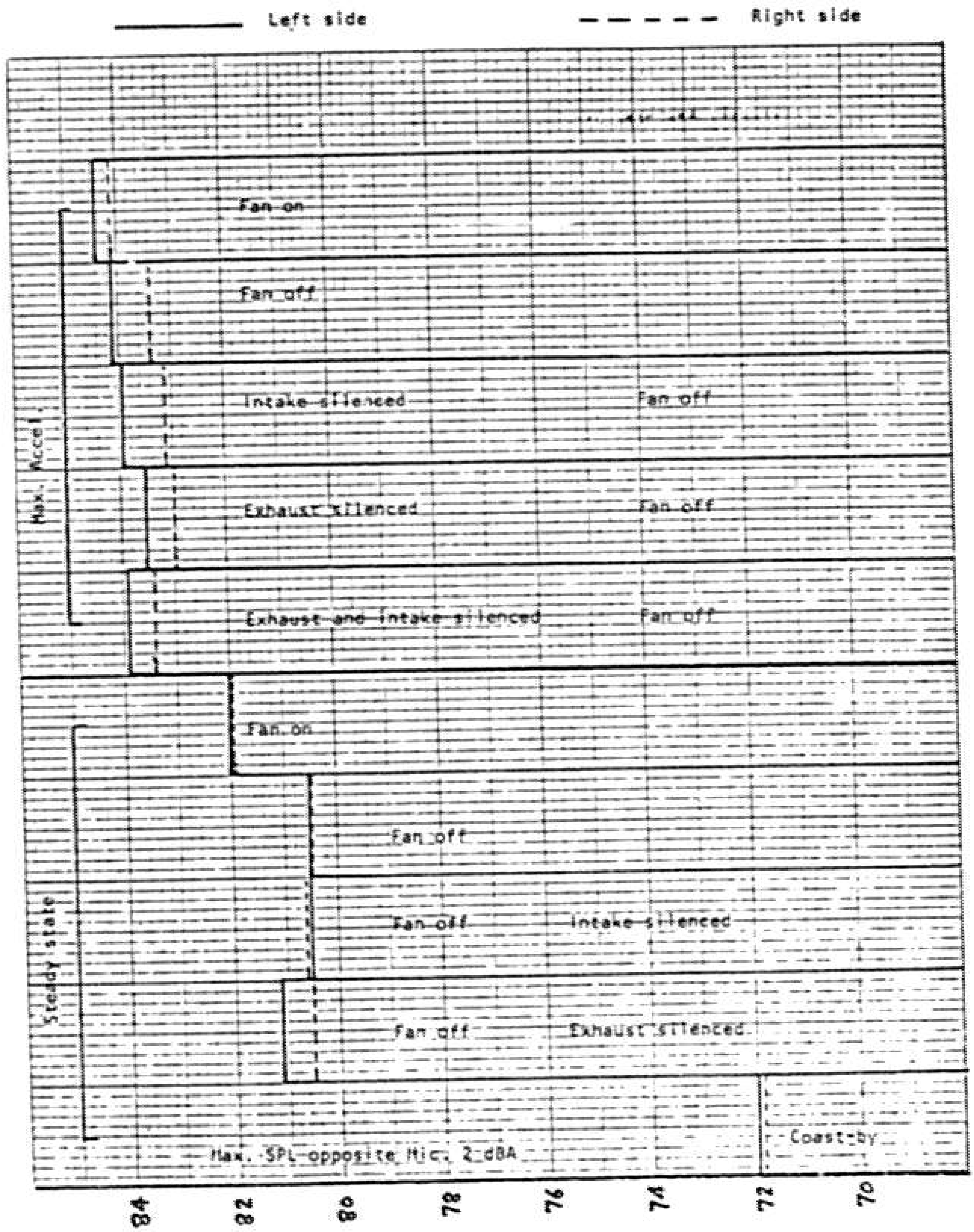


FIGURE 2-30. PEUGEOT - NOISE SOURCE TESTS (DRIVE-BY)

ENTRY SPEED : 30 mph

2ND GEAR

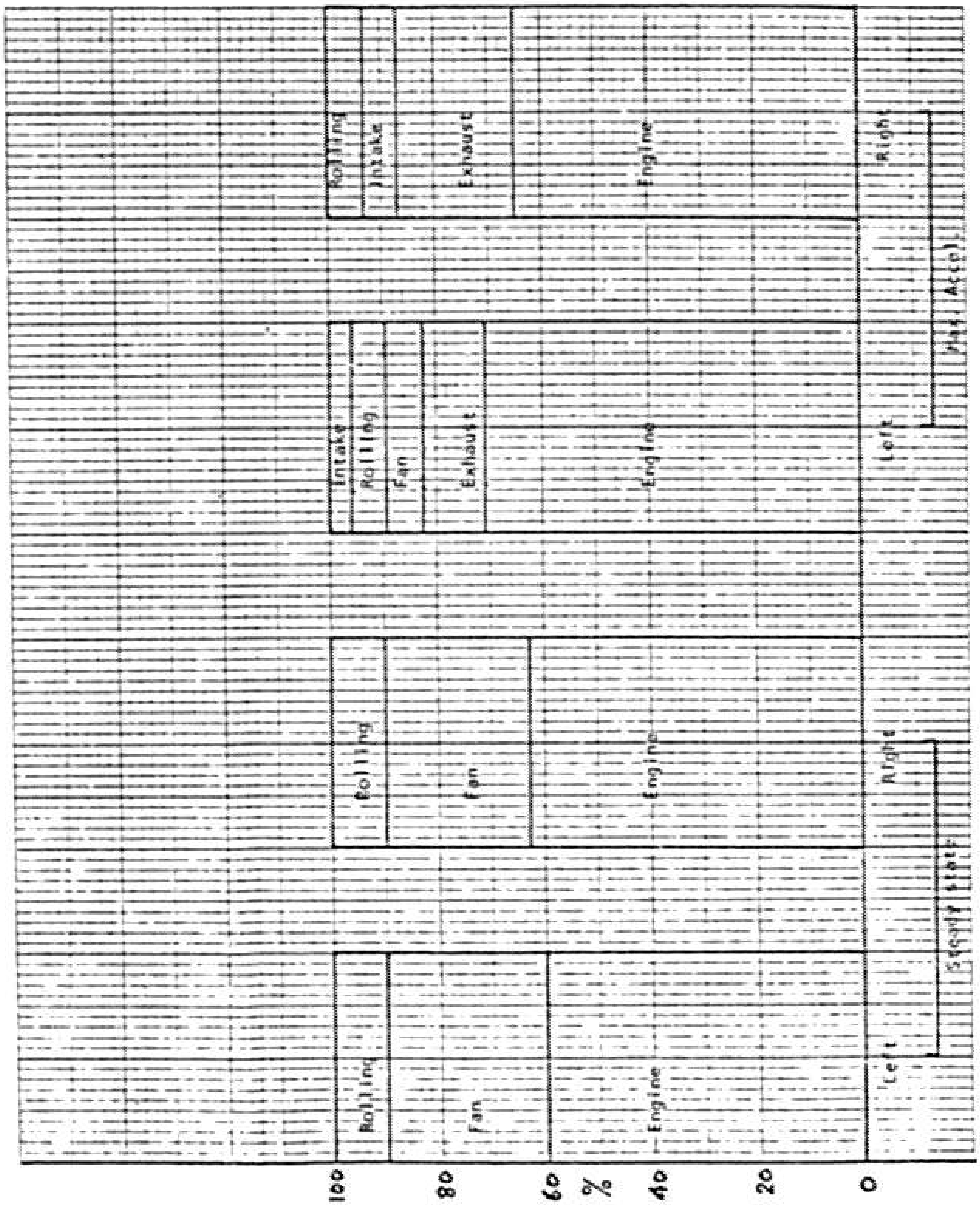


FIGURE 2-31. PEUGEOT - NOISE SOURCE BREAKDOWN (ON DRIVE-BY) BASIS)

AS FUNCTION OF CONSTANT ROLLING NOISE   ENTRY SPEED : 30 mph

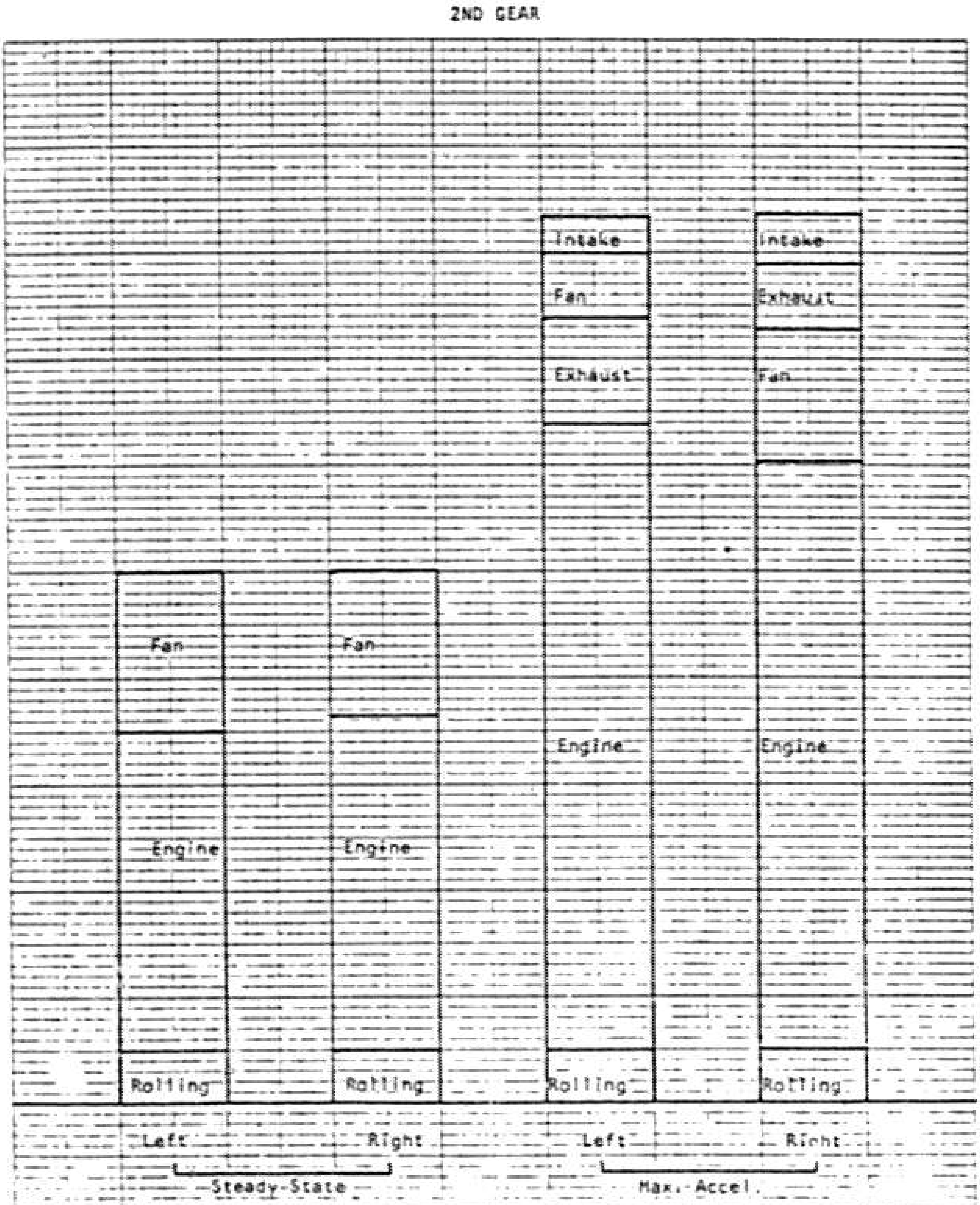


FIGURE 2-32. PEUGEOT - NOISE SOURCE BREAKDOWN (ON DRIVE-BY BASIS)

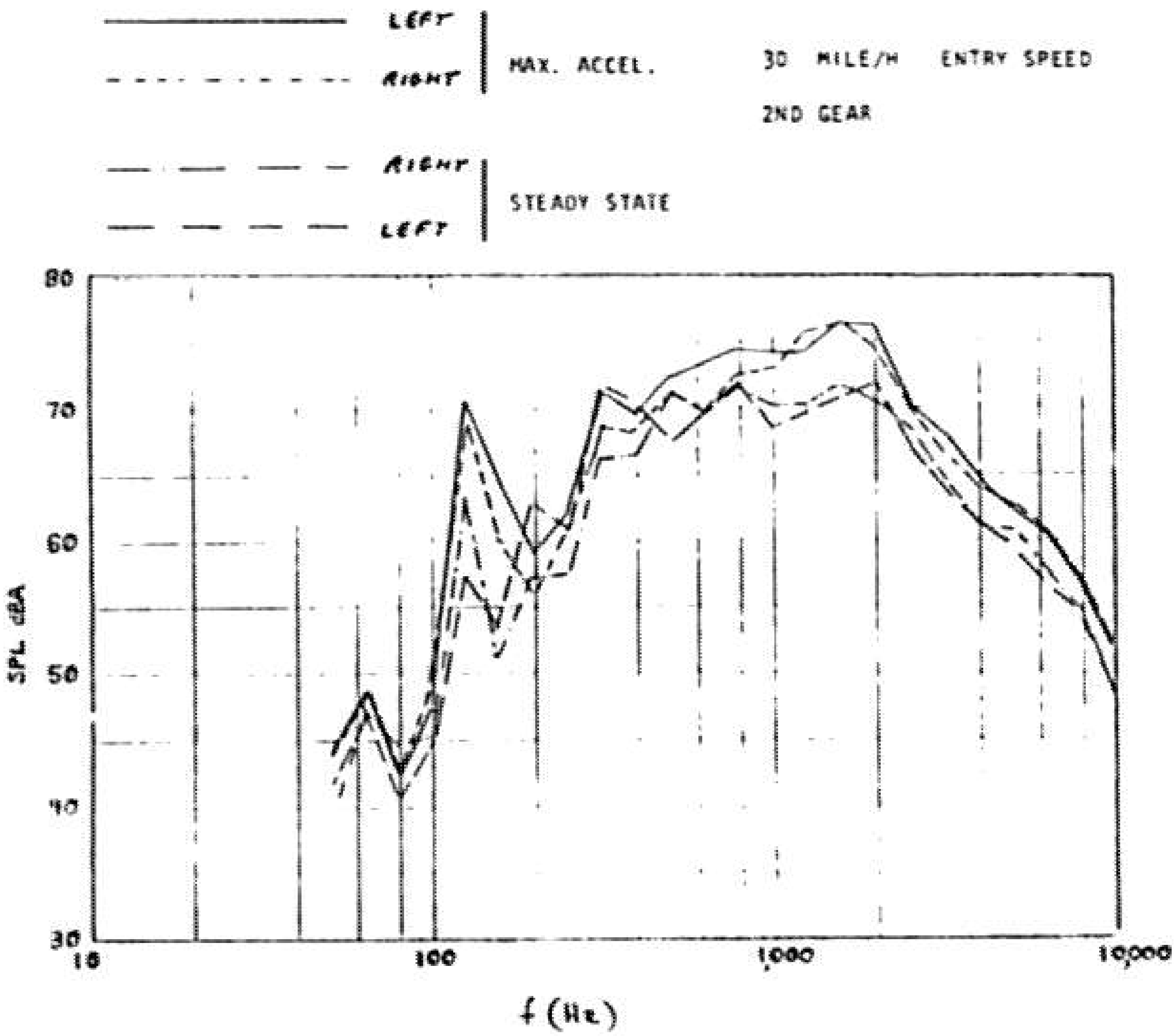


FIGURE 2-33. PEUGEOT - MAXIMUM DRIVE-BY SPECTRA AT MIC. 2

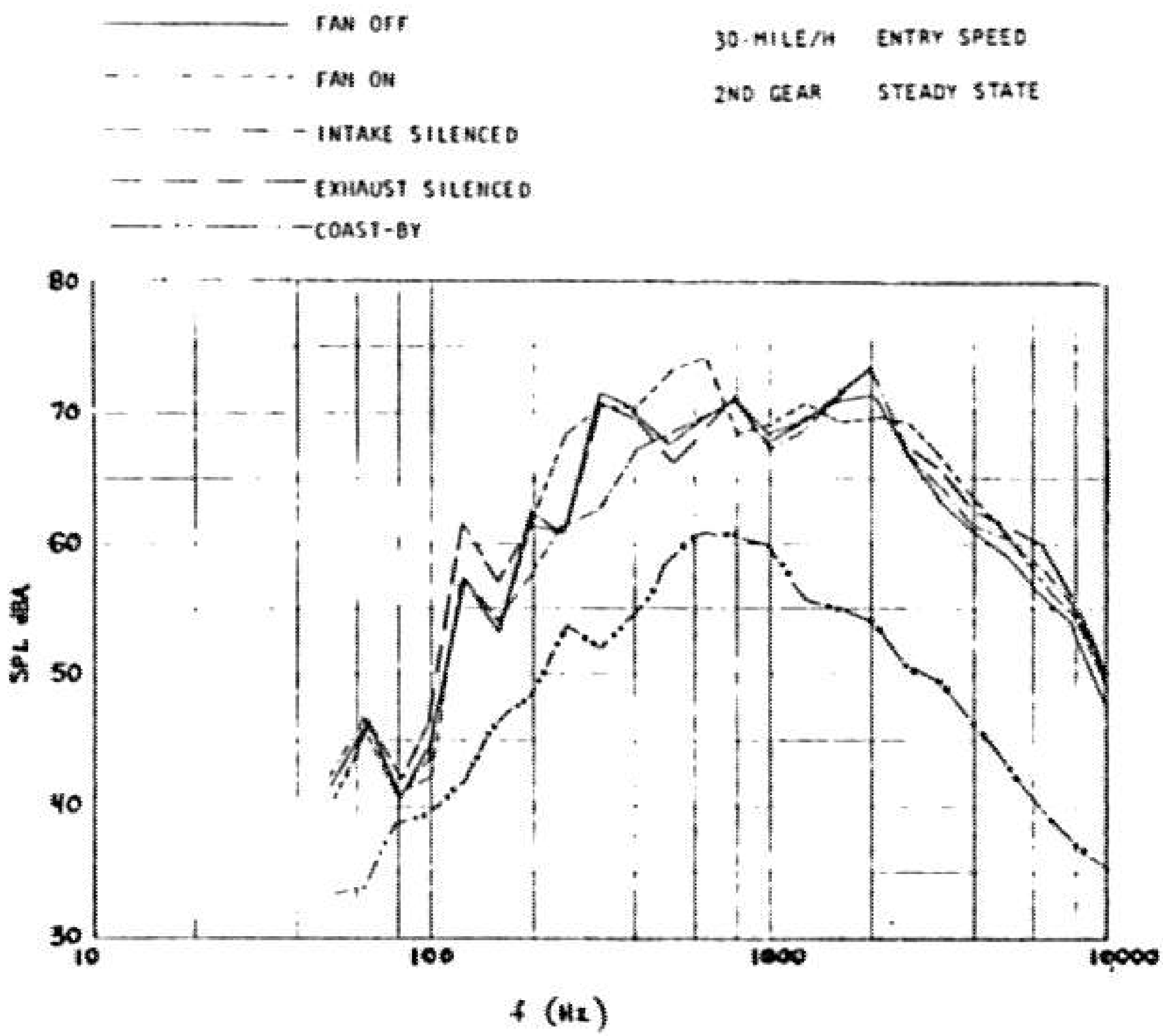


FIGURE 2-34. PEUGEOT - NOISE SOURCE TESTS DRIVE-BY SPECTRA (MAXIMA AT MIC.2)

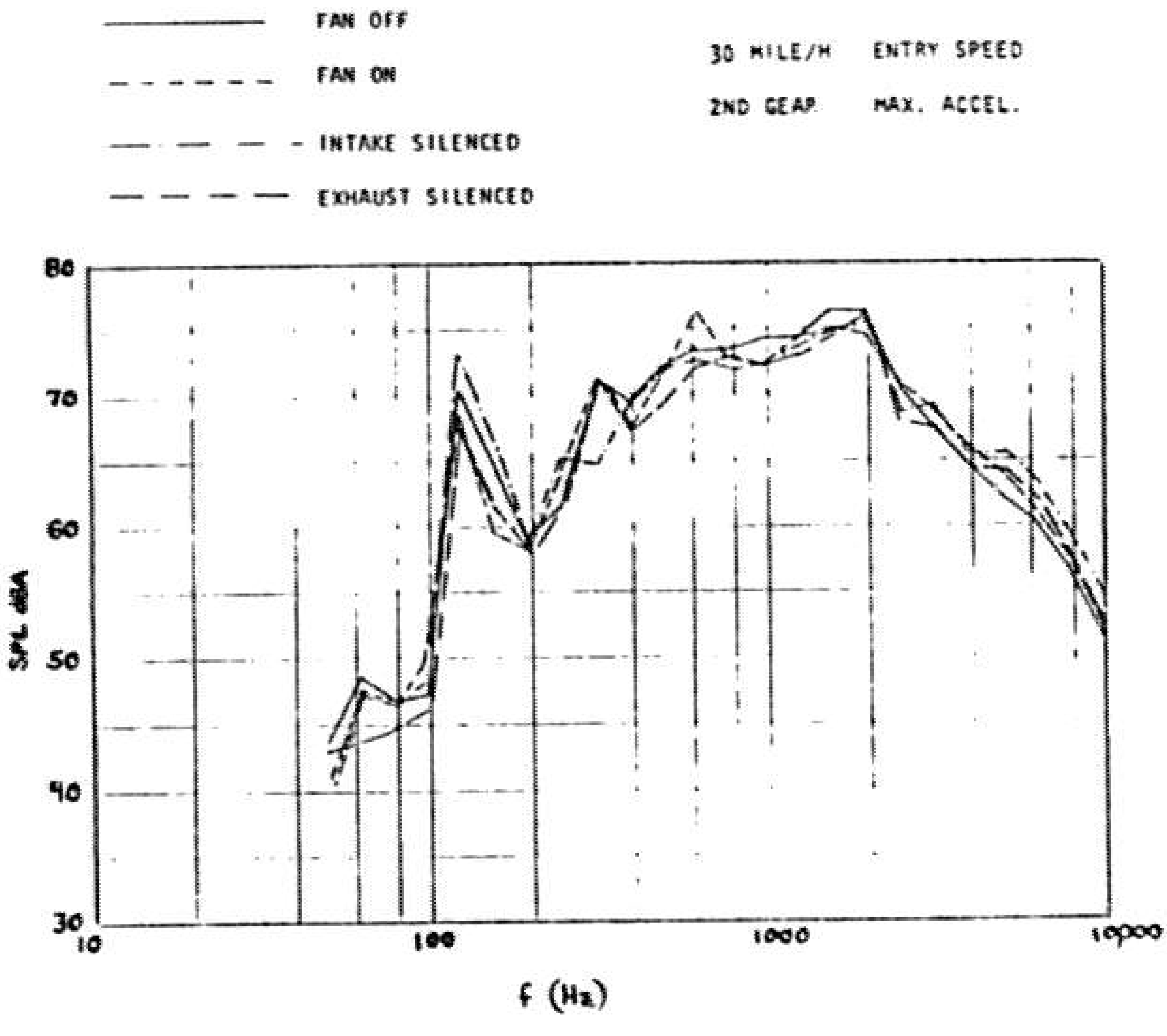


FIGURE 2-35. PEUGEOT - NOISE SOURCE TESTS DRIVE-BY SPECTRA (MAXIMA AT MIC. 2)

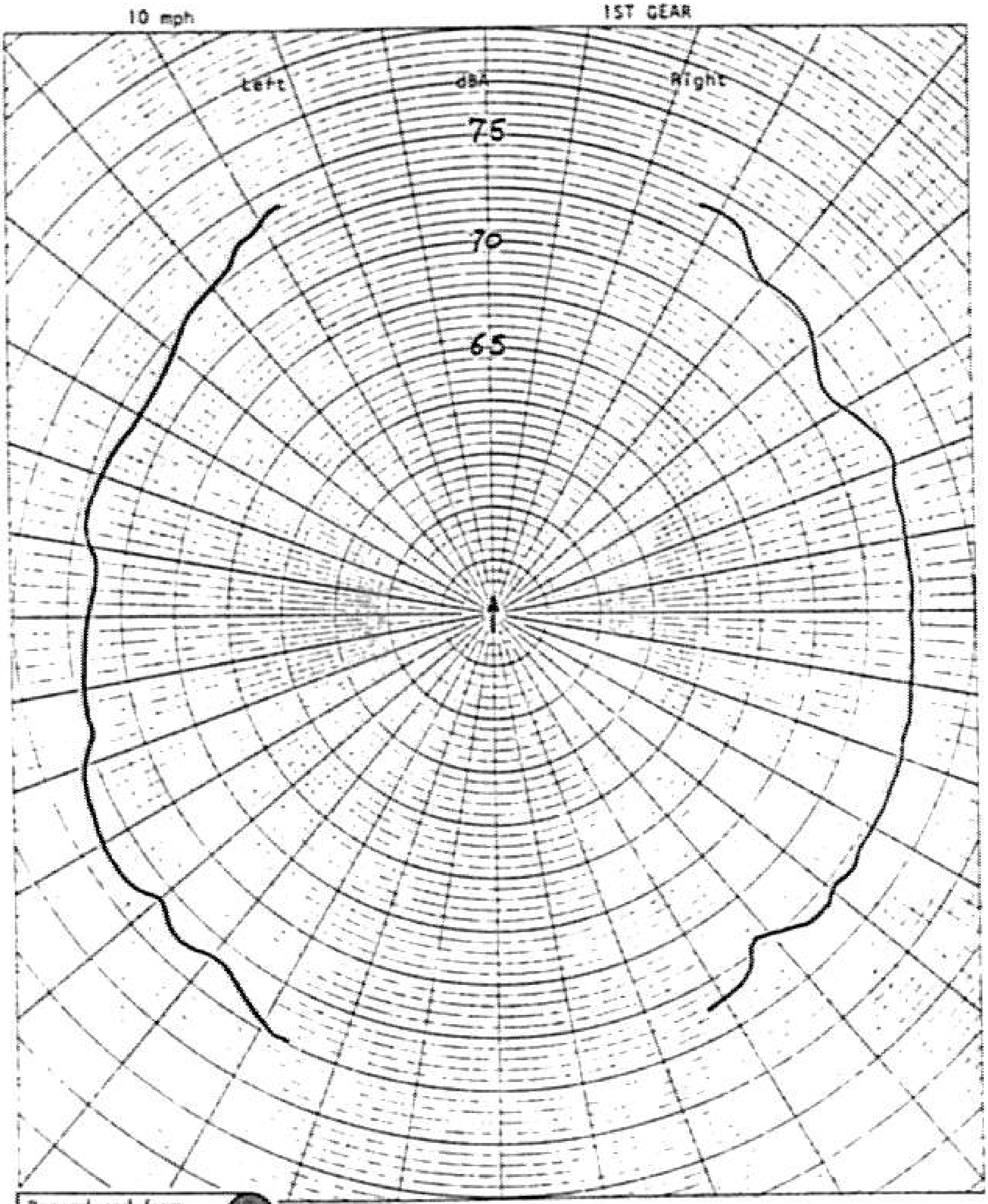


FIGURE 2-36. PEUGEOT - POLAR NOISE DISTRIBUTION FROM DRIVE-BY TEST SPL NORMALIZED TO 7.5m

20 mph 2ND GEAR

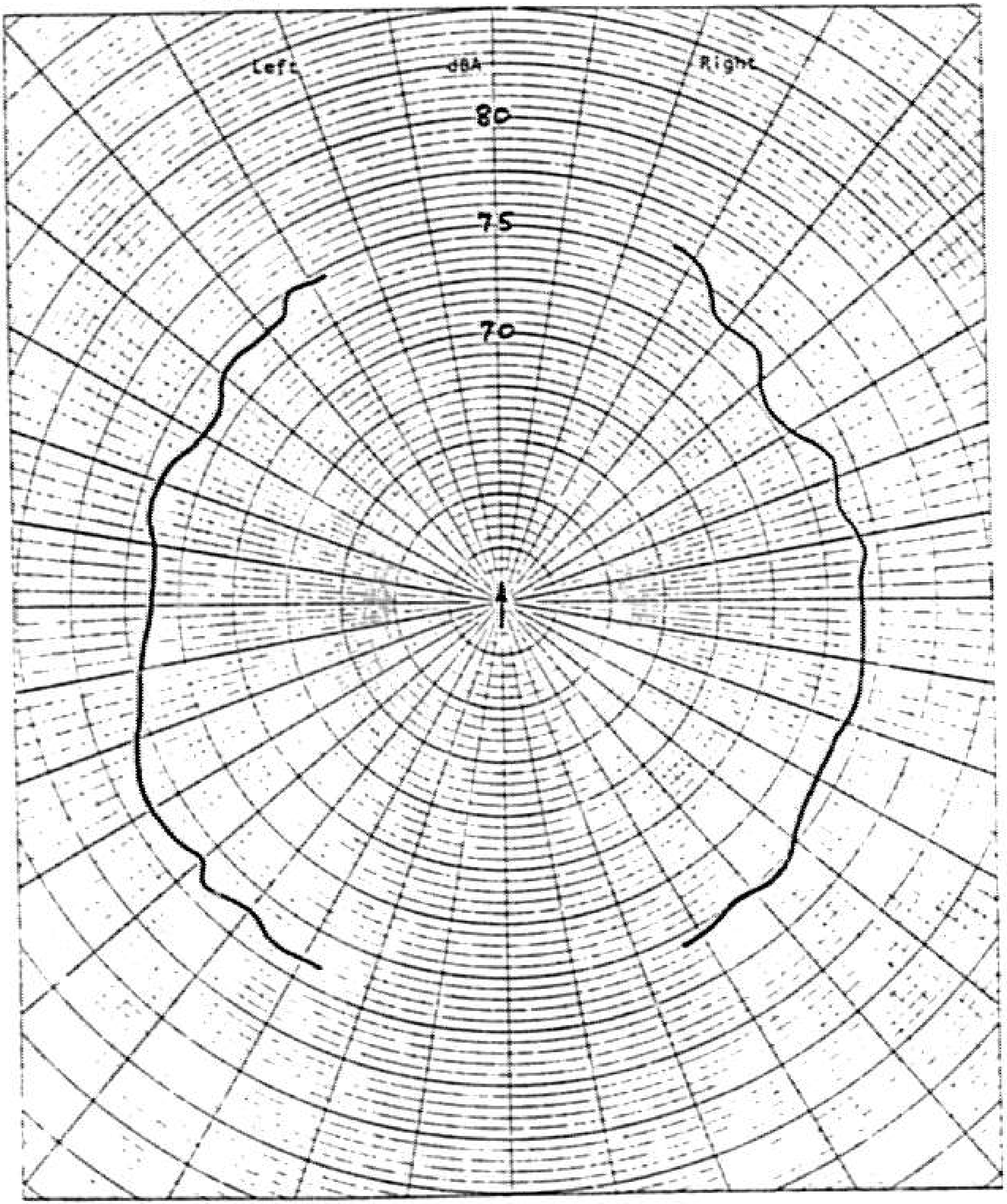


FIGURE 2-37. PEUGEOT -POLAR NOISE DISTRIBUTION FROM DRIVE-BY TEST SPL NORMALIZED TO 7.5m

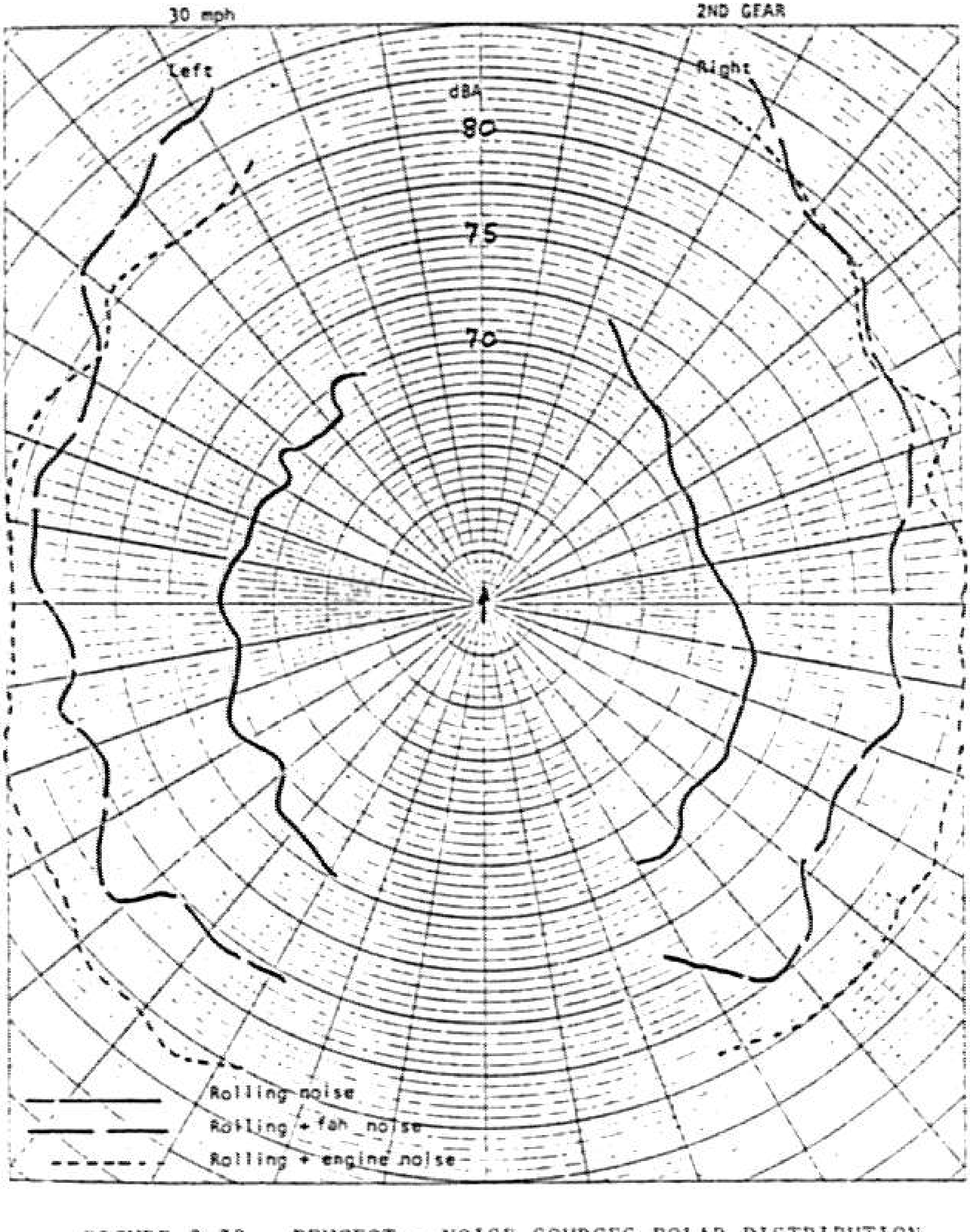
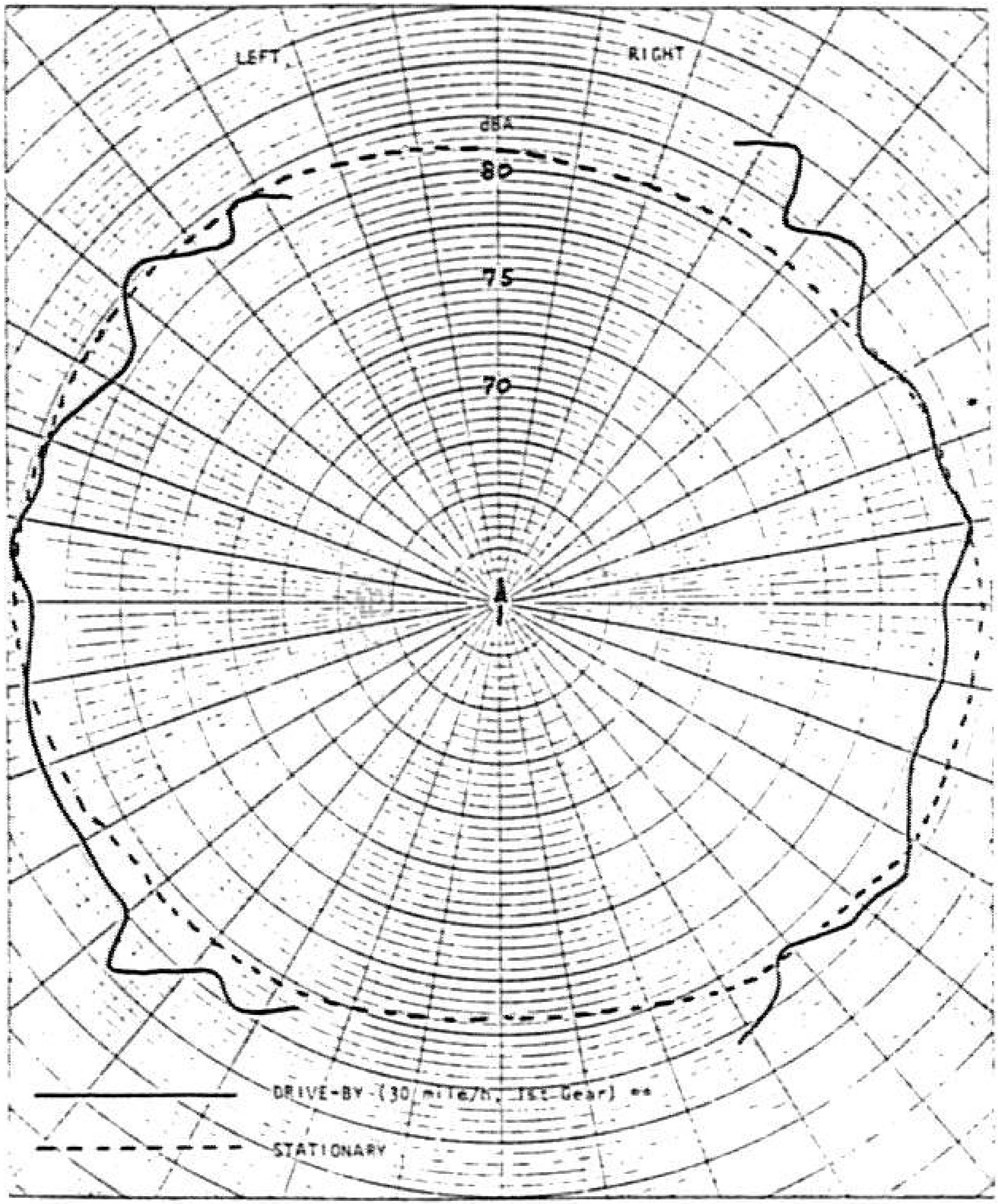


FIGURE 2-38. PEUGEOT - NOISE SOURCES POLAR DISTRIBUTION FROM DRIVE-BY TESTS SPL NORMALIZED TO 7.5m

ENGINE SPEED 95 rev/s



** ROLLING NOISE DEDUCTED

FIGURE 2-39. SAAB - DRIVE-BY POLAR NOISE DISTRIBUTION COMPARED WITH STATIONARY POLAR NOISE

ENGINE SPEED : 63 rev/s

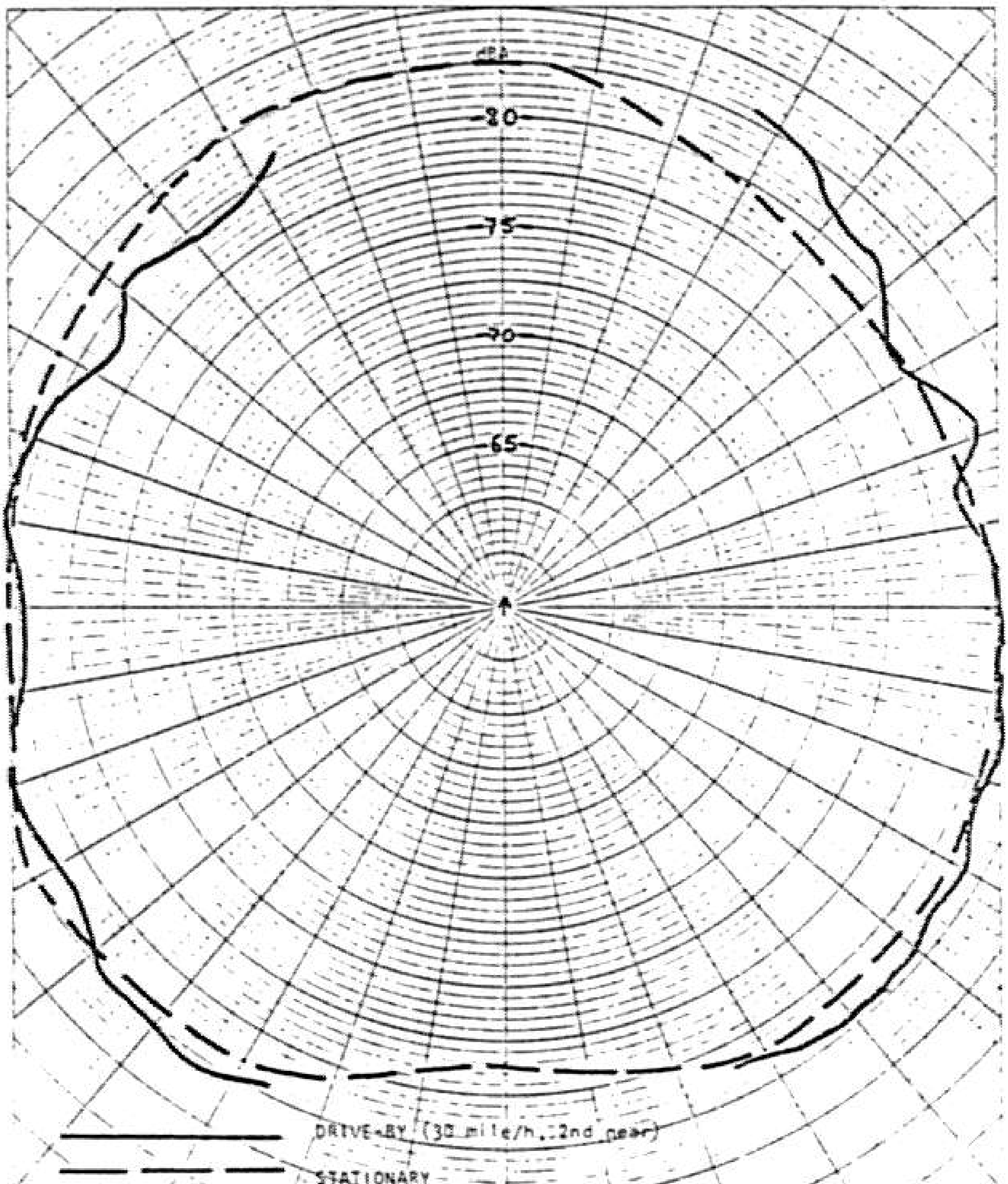


FIGURE 2-40. PEUGEOT - DRIVE-BY POLAR NOISE DISTRIBUTION COMPARED WITH STATIONARY NOISE

MIC. POSITIONS AS IN FIG.42

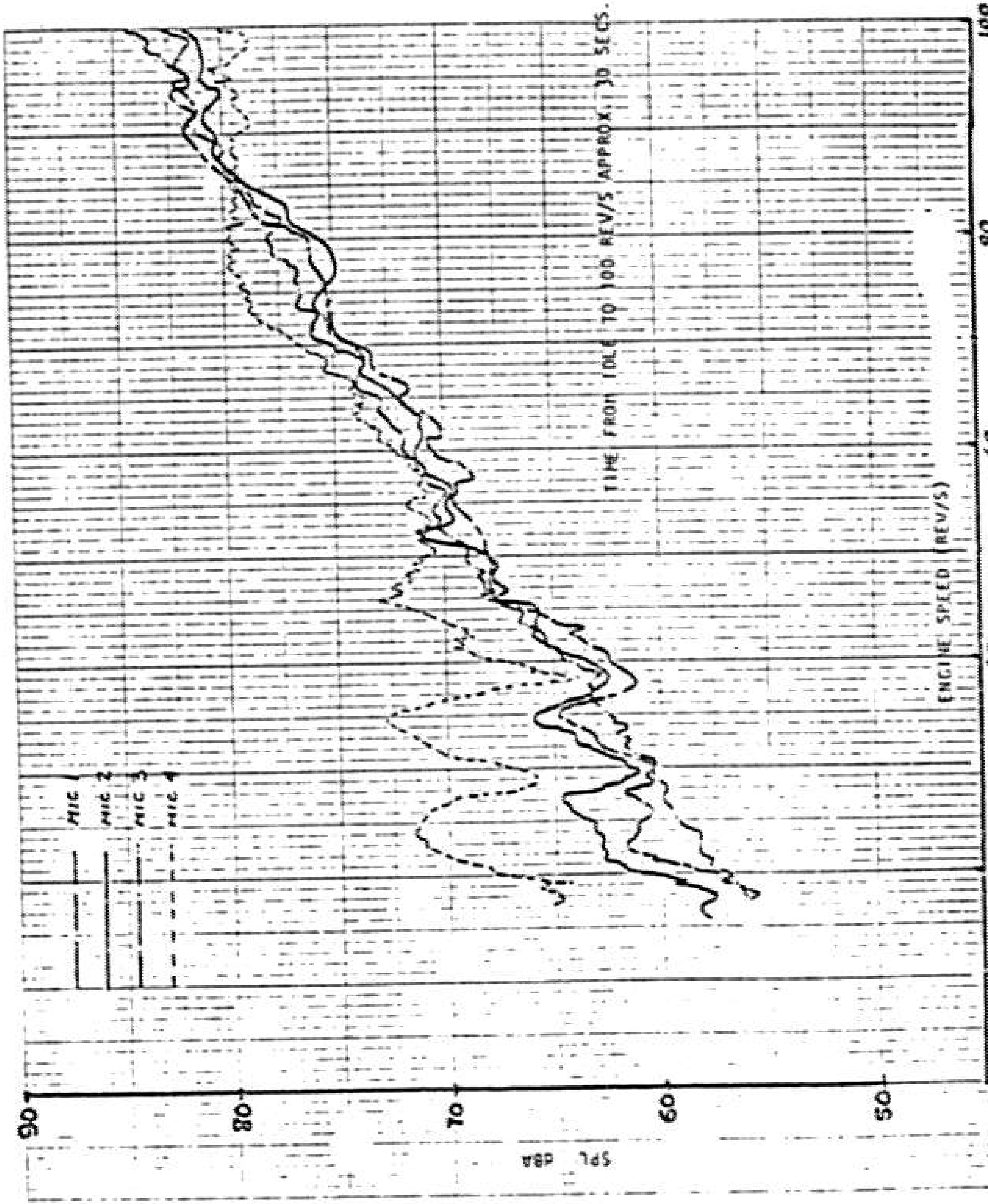


FIGURE 2-41. SAAB - EXHAUST AND ENGINE NOISE V ENGINE SPEED VEHICLE STATIONARY

Mic. HEIGHT. : 1.2m

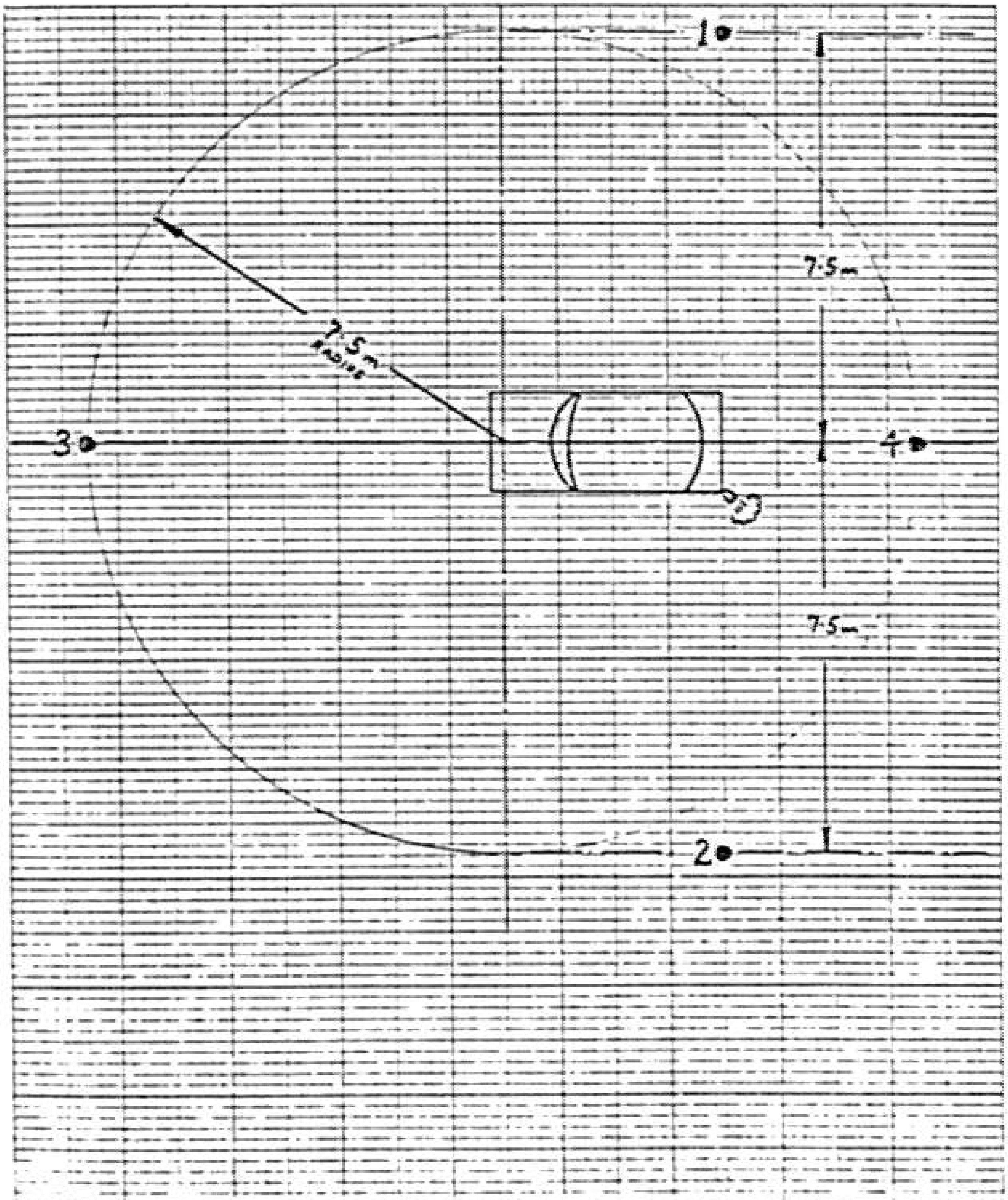


FIGURE 2-42. SAAB - MICROPHONE POSITIONS FOR EXHAUST NOISE V ENGINE SPEED STATIONARY TEST

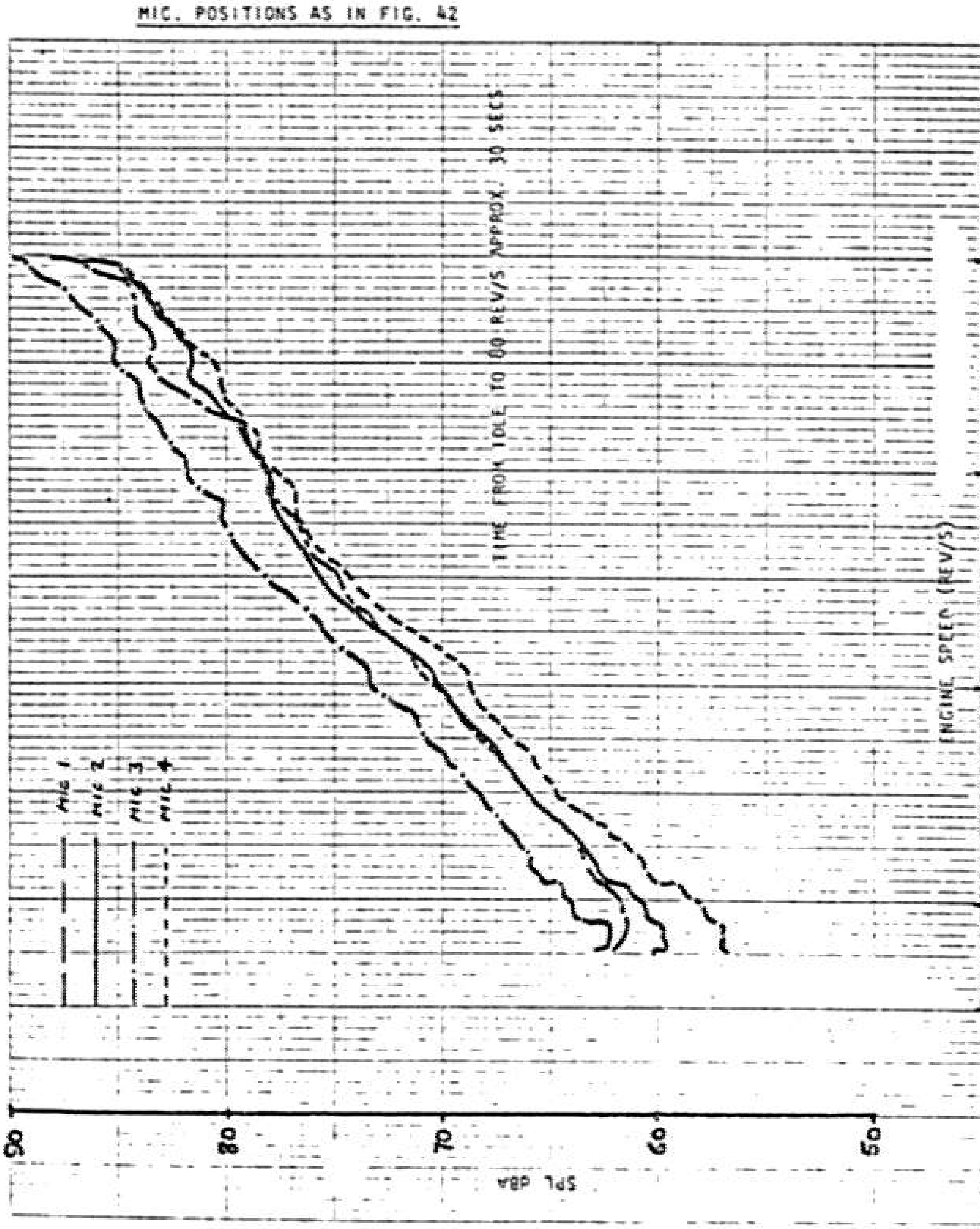


FIGURE 2-43. PEUGEOT - EXHAUST AND ENGINE NOISE V ENGINE SPEED VEHICLE STATIONARY

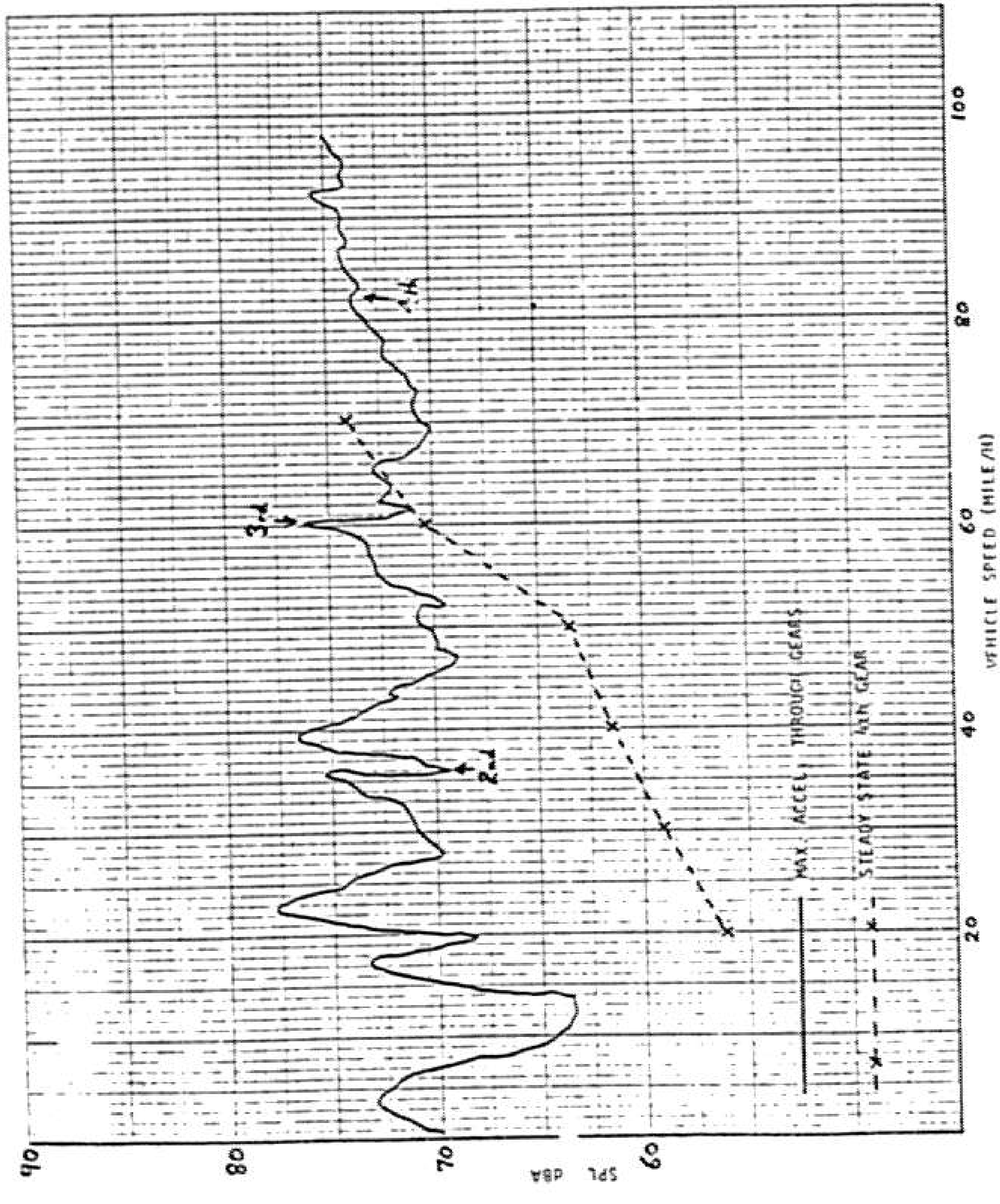


FIGURE 2-44. SAAB - INTERIOR NOISE (MEASURED AT DRIVER'S EAR POSITION)

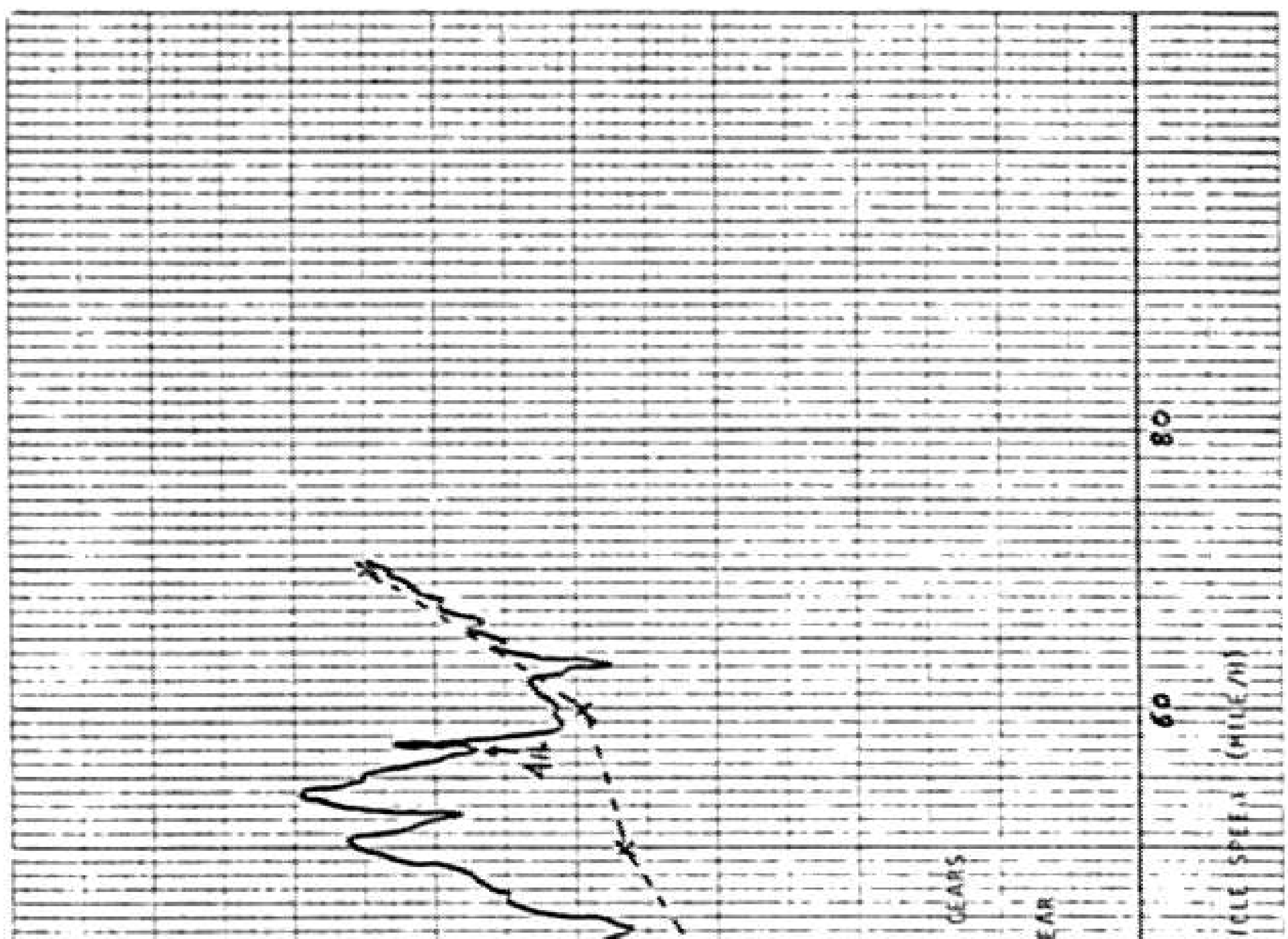


FIGURE 2-45. PEUGEOT INTERIOR NOISE (MEASURED AT DRIVER'S EAR)

ENTRY SPEED : 31 MILE/H

2nd GEAR

LEFT SIDE

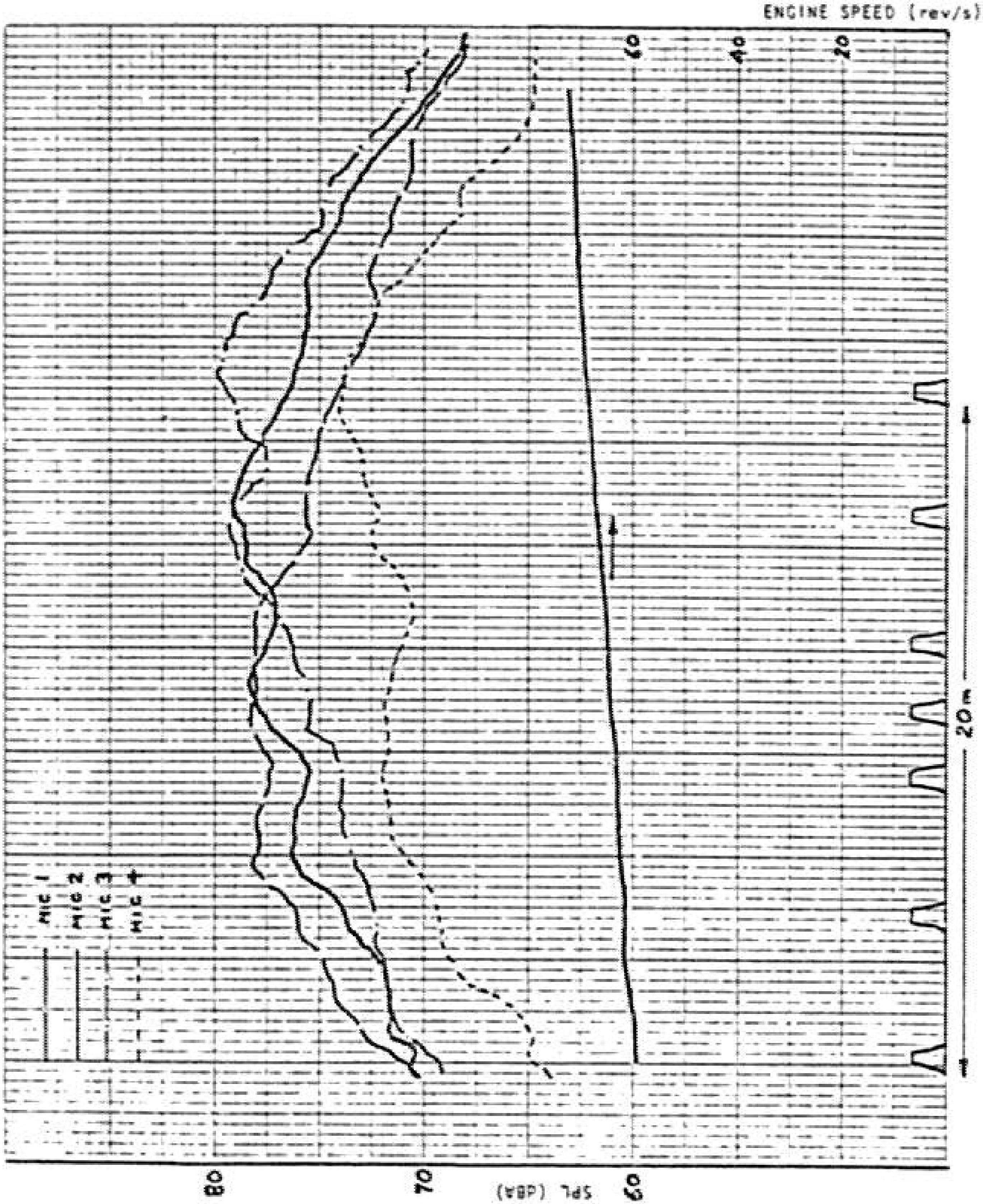


FIGURE 2-46. SAAB - ISO DRIVE -BY

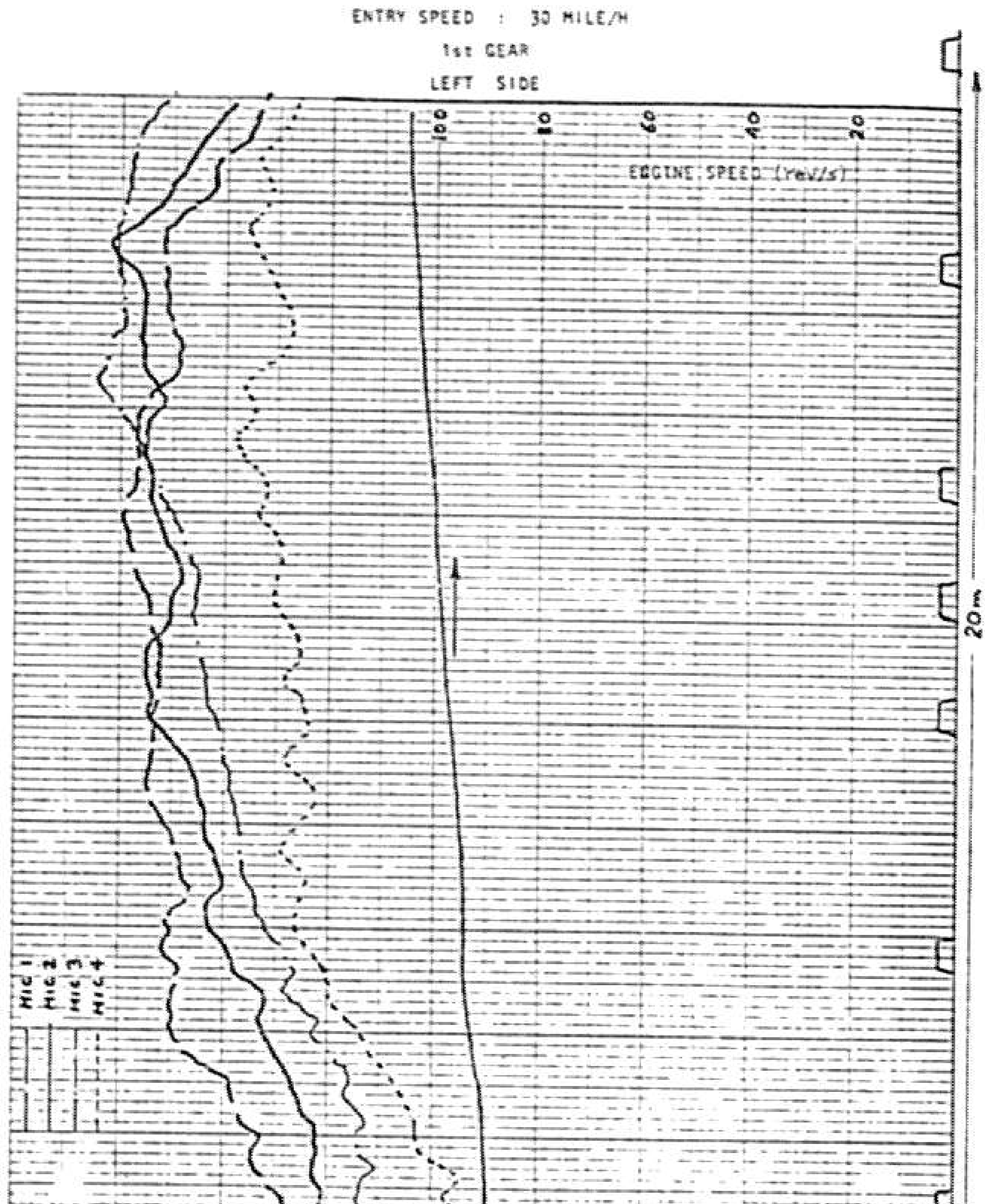


FIGURE 2-47. SAAB - SAE DRIVE-BY

ENTRY SPEED : 30 MILE/H

2nd GEAR

LEFT SIDE

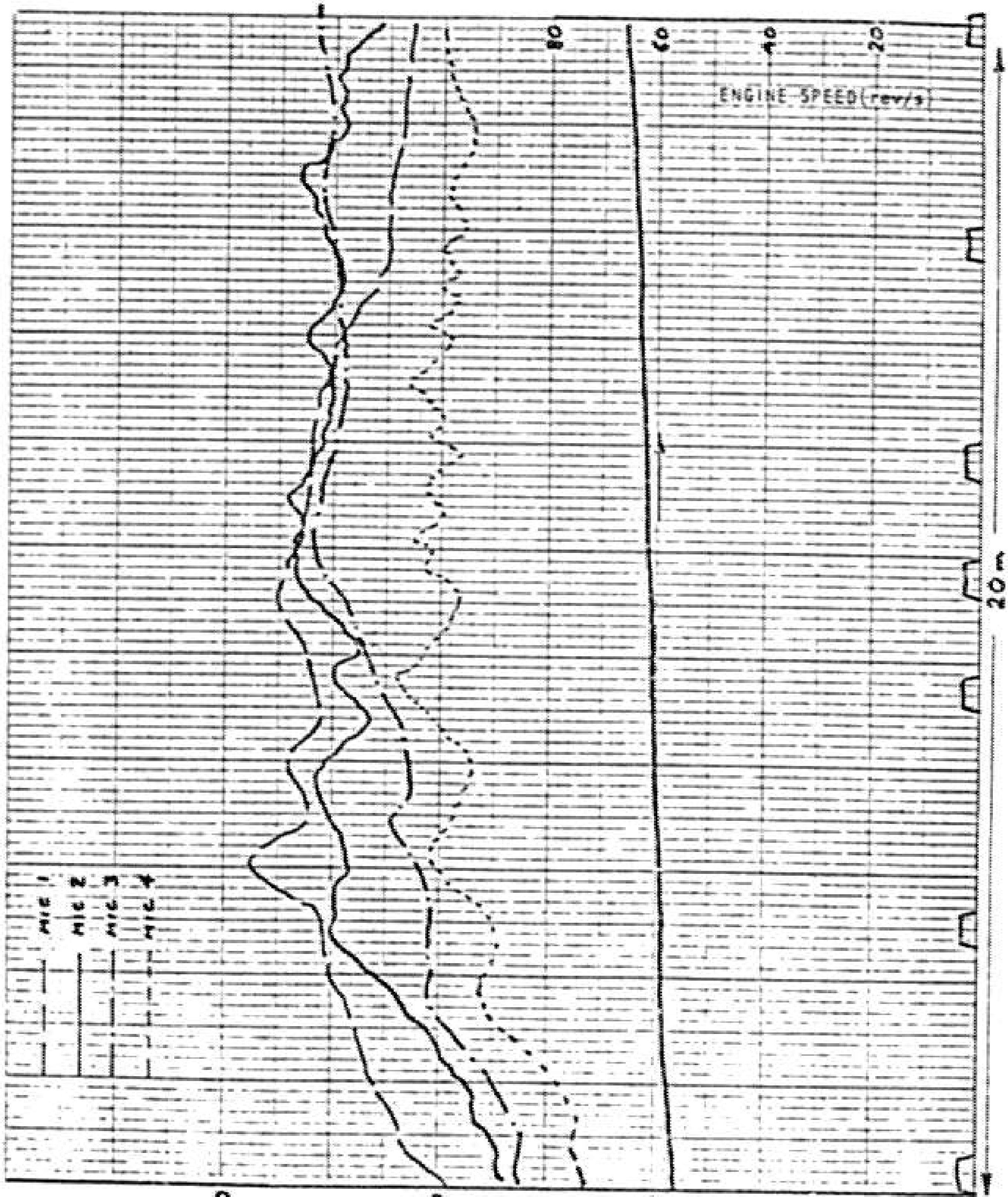


FIGURE 2-48. SAAB - SAE DRIVE-BY

ENTRY SPEED : 28 MILE/H

2nd GEAR

LEFT SIDE

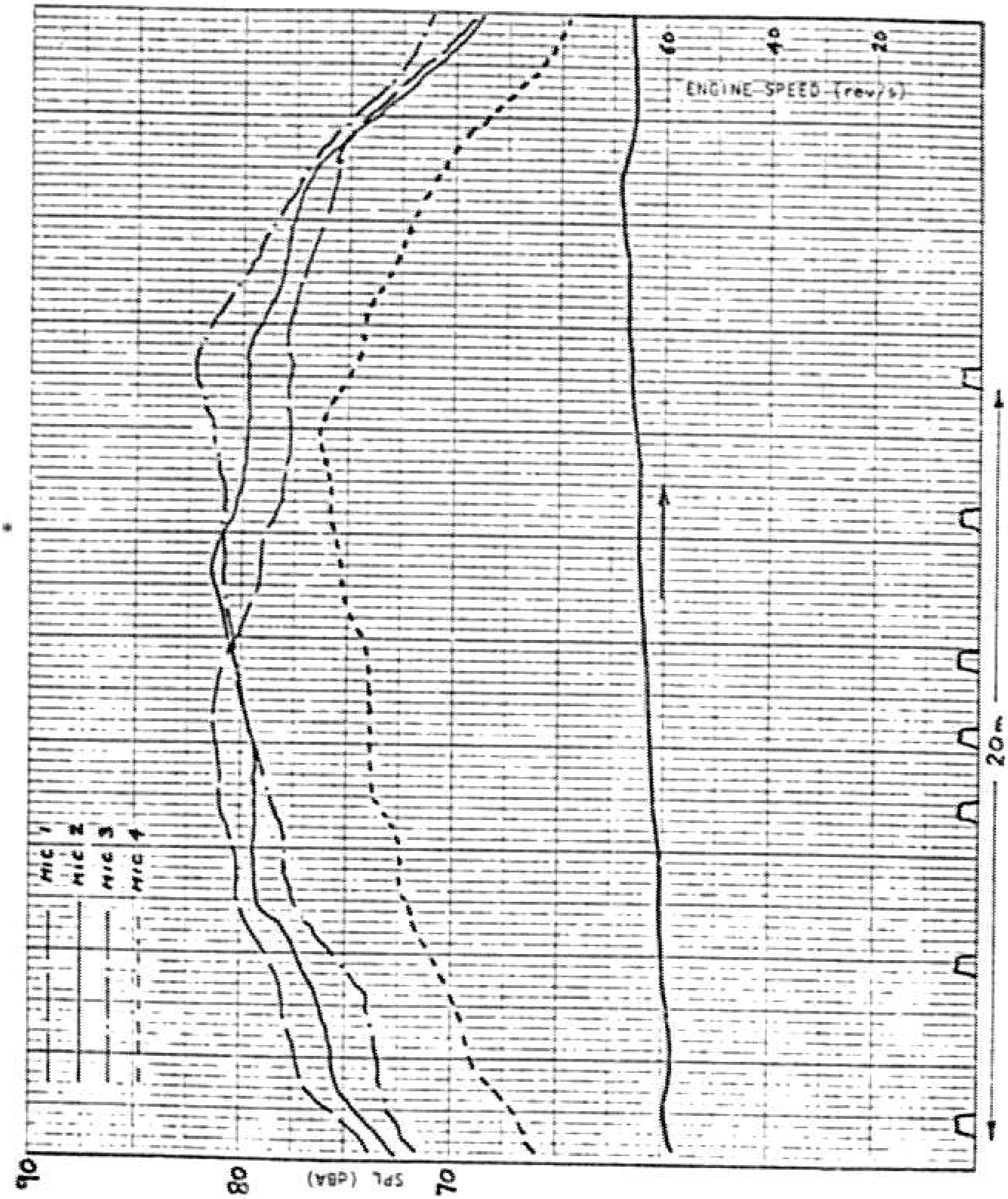


FIGURE 2-49. PEUGEOT · ISO DRIVE-BY

ENTRY SPEED : 30 MILE/H

2nd GEAR

LEFT SIDE

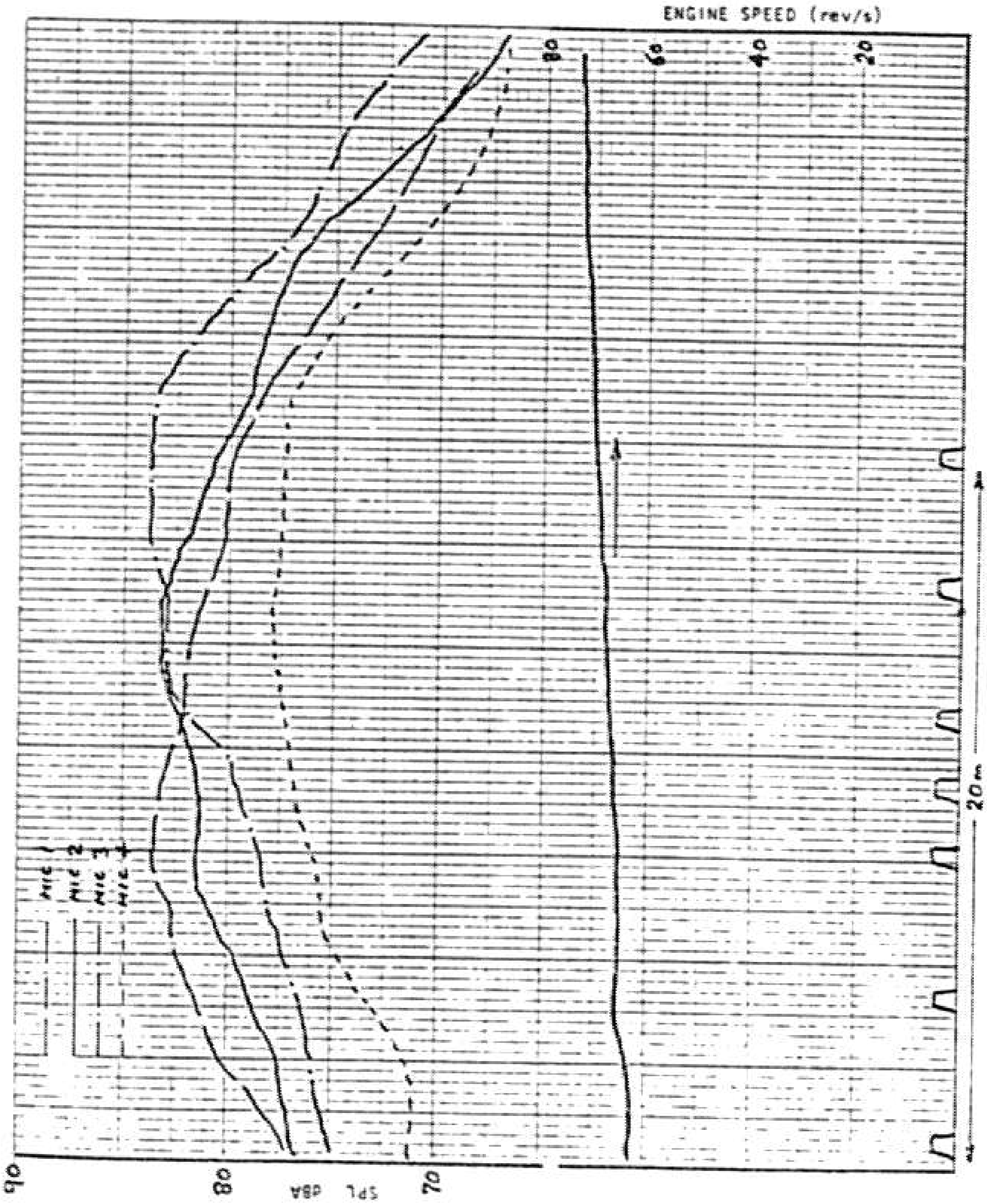


FIGURE 2-50. PEUGEOT - SAE DRIVE-BY

3. NOISE TESTS ON A SELECTION OF EUROPEAN PASSENGER CARS

3.1 INTRODUCTION

The work described in this report forms a part of the program for DOT/TSC being carried out for the prime contractor, Calspan Corporation, to evaluate European highspeed engine noise characteristics. A detailed noise evaluation program has already been conducted on the Saab 99 GL Injection and Peugeot 504 GLD vehicles (summarized in Ricardo report DP 77/1158). In order to supplement this information, nine standard European passenger cars (plus one prototype) were selected and a number of drive-by and interior noise tests carried out. The drive-by tests were conducted on the same site as that used for the Saab and Peugeot and the same four microphone array and vehicle position indicating system used. The signals from the four microphones were recorded simultaneously on a seven channel FM tape recorder and subsequently processed in analogue form by means of an X-Y plotter. The test site was calibrated before use by means of a noise source traversed along the zone center line. Sound pressure level fall-off rates were close to the expected -6dBA per doubling of distance with an overall mean value of -5.9 dBA per doubling. The interim report DP 77/1158 outlines the Saab and Peugeot tests; the following report is a detailed report on the ten additional vehicles and also includes the Saab and Peugeot tests where relevant for comparison. Reports covering the Saab and Peugeot engine tests under anechoic conditions will be issued on completion of the program.

3.2 VEHICLES TESTED

Three main criteria were applied in the selection of the ten vehicles: power/weight ratio, how representative the vehicles were of their class and the market penetration based on volume sales. In addition some consideration was given to availability. A wide spread of power/weight ratios was called for and this was well spanned from the lowest ratio (0.022 bhp/lb) to the highest ratio (0.055 bhp/lb). The nominal ratios were derived from the manufacturers DIN bhp engine power and the vehicle curb weight. Figure 3-1 shows the spread of power/weight ratios of a wide range of European cars.

The popularity of a vehicle was judged by the market sales figures available for Western Europe as a whole for the first seven months of 1977. These figures are shown below. (Note: The selection of the cars and the test work was carried out in late 1977).

	Vehicle	No. of Cars	% of Market
1.	Fiat 127	294,000	4.8
2.	Ford Cortina/Taunus	264,000	4.3
3.	V.W. Golf ('Rabbit')	246,000	4.0
4.	Renault 5	235,000	3.8
5.	G.M. Chevette/Kadett	227,000	3.7
6.	Ford Fiesta	192,000	3.1
7.	G.M. Ascona/Cavalier	189,000	3.1
8.	Renault 4 & 6	183,000	3.0
9.	V.W. Polo/Derby	149,000	2.4
10.	Chrysler 1307/8/Alpine	147,000	2.4

The highest ranked Japanese car was at 30th position and was the Toyota Corolla.

All the additional vehicles were saloon cars, tested as received in normal U.K. production build. Most of the cars were less than twelve months old but none more than two years old. All were run-in and in normal working order. Eight of the ten vehicles were gasoline engine powered. The remaining vehicles were diesel engine powered (one being a prototype turbocharged diesel passenger car). The vehicles selected are listed below in ascending order of power/weight ratio together with brief reasons why that particular vehicle was chosen.

A description of each vehicle is given in Table 3-1. (Note that for all tables the vehicles are listed in ascending power/weight ratio) and the vehicles are illustrated in Appendix 1.

a) Renault 4TL

This was chosen as representing the lowest power/weight ratio category. It is also extremely popular in France and in Europe as a whole, ranking No. 4 in the top ten list; over 5 million have been made.

b) Opel 2100D

This was the naturally aspirated diesel version of the Opel 2100 and was chosen for comparison with the Peugeot and also with a prototype turbocharged version (see d below).

c) Ford Fiesta I

An increasingly popular car in the under $60in^3$ class is the so-called 'hatchback' (e.g. V.W. Polo, Renault 5, Peugeot 104, Fiat 127). The Fiesta was chosen as one of the most recent of this type and one which is proving to be extremely popular.

d) Opel 2100D T/C

This was not a standard production vehicle, but a Ricardo experimental turbocharged version of b) above. Apart from the addition of the turbocharger, however, the vehicle was identical in all important aspects to the production car. This car was chosen because of the increasing popularity of the light-duty diesel vehicle and the interest being shown in achieving acceptable performance by turbocharging, with minimal fuel consumption increase.

e) Cortina 1600

The Cortina is the best selling car (based on volume sales) in the U.K. and No. 2 in Western Europe as a whole, is available in many different trims and with many different power units. The 1600 (97 in^3) was chosen as being the most representative.

f) Vauxhall Chevette GL

The Chevette represents a very popular small car in the 'hatchback' vehicle category in the 80 in^3 and above class (others being the V.W. Golf, Honda Civic, Chrysler Sunbeam and Mazda Hatchback) and has been widely recognized as one of the best designed and engineered small cars to be produced by Vauxhall Motors. Together with the Opel Kadett, (a GM model in the same class as the Chevette) some 3.7 percent of the European market is held by these models.

g) Alpine S

The Chrysler Alpine, as it is known in the U.K. (Simca 1308 in France) was nominated European Car of the Year in 1976 and was chosen as the basis for the Calspan Research Safety Vehicle program. It was also No. 10 in the European sales chart. The higher powered 'S' version (88 in^3 engine) was selected mainly to fill a gap in the power/weight ratio speed.

h) Volvo 244 GL

The Volvo, a car with a reputation for reliability, durability and solidness of construction, is a popular choice in the intermediate-luxury class of European passenger car. The vehicle tested was the fuel injected version of the 130 in^3 engine as this particular vehicle was immediately available.

i) Jaguar XJ6 4.2

The Jaguar is well known for its performance, sophistication and general high quality. The XJ6 is particularly noted for its effortless high-speed cruising ability with minimal interior noise. The 258 in^3 version tested was immediately available and represented a high power/weight ratio class of vehicle.

j) Triumph Dolomite Sprint

Apart from one or two specialist saloon cars (e.g. certain BMW models) it was difficult to find a typical European car of very high power/weight ratio without resorting to the very high performance sports cars (e.g. Porsche, Ferrari). Such vehicles would hardly be representative on a mass noise impact basis. The Dolomite Sprint was therefore chosen as it is basically a very orthodox family saloon in many aspects apart from the power train. The extensively modified 122 in^3 engine produces a nominal 127 bhp, far in excess of most of the other available engines which normally power the Dolomite (typically 70 bhp).

The above vehicles were tested as-received. Most of the cars had mechanically driven fans, either directly or through a viscous coupling. No modifications were made to these fans. The only cars with electrically driven fans were the Ford Fiesta and Chrysler Alpine S. For the Fiesta, the fan was not thermostatically controlled but remained on. The Fiesta was tested in this condition. The Alpine S fan was thermostatically controlled and therefore would cut in or out according to the engine condition. This fan was therefore disconnected and all drive-by tests were made on this car with the fan off. (A check drive-by test with the fan on was later carried out and no detectable difference measured. This was also the case with the Saab, where the electrically driven fan noise was negligible on a drive-by test).

3.3 TEST PROGRAM

The test program consisted of a) a series of drive-by noise tests, b) interior noise measurements, c) exterior noise measurements with the vehicle stationary and engine idling. Details of each part of the program are given below.

3.3.1 Drive-by Tests

The drive-by site was the same as that used for the Saab and Peugeot tests and is shown schematically in Figure 3-2. The vehicle position indicating and noise recording system was also as used for the Saab and Peugeot tests and is outlined in Ricardo report DP 77/1158. A transferable spotlight package was fabricated which could be rapidly adapted to fit most types of vehicle. This triggered the seven vehicle position indicators alongside the 20m test zone. Before commencing the tests, the car speedometer was calibrated by timing over a measured half mile.

A sufficient number of runs were carried out for each test to obtain an accepted repeatability at microphone 2 position (for a given side of the vehicle) of within <1 dBA. Both left and right sides of the vehicle were measured.

The following tests were carried out for each vehicle.

a) <u>ISO Test (to ISO R363 equivalent to 70/157/EEC)</u>

For this test, the entry speed was 31 mile/h (50km/h) or the speed corresponding to 3/4 rated engine speed (i.e. at which the engine reaches maximum power) in 2nd gear, whichever was the lower. The gear selected in all cases was 2nd, none of the vehicles having more than four forward ratios (the overdrive unit on the Dolomite Sprint was not engaged). For the Jaguar, the only car tested with automatic transmission, D2 was selected. Table 3-2, shows the entry speeds used for each car and gear ratio data. The test was carried out according to ISO requirements, that is opening the throttle (or rack, in the case of the diesel cars) fully as the front of the car enters the 20m zone.

b) <u>'Maximum' ISO Test</u>

This test was selected as an indication of the influence of engine noise at rated engine speed, by ignoring the effects of gear ratio (except on the second order noise effect of vehicle speed) and choosing an entry speed for each vehicle which would enable rated engine speed to be achieved at the zone exit. Table 3-2 shows the zone entry and exit speeds required to meet this criterion. Second gear was used in all cases except for the Jaguar where the limitations of the site (and legal requirements) prohibited the use of D2 (an entry speed of approx. 70 mile/h would have been necessary). Thus D1 was used in this case. The test was maximum acceleration test, fully opening the throttle (or rack in the case of the diesel vehicle) at the beginning of the zone.

c) Maximum acceleration - Entry Speed 10 mile/h - 1st gear

This test allowed a wide engine speed range to be evaluated as the car accelerated to near maximum engine speed at the end of the zone. Any particular sensitivity of exhaust noise to engine speed would also show up during this wide engine speed range.

d) Steady state - Entry speed 30 mile/h - 2nd gear

This condition represents a significant part of European urban driving and would therefore give an indication of cruising noise impact to a roadside observer.

f) Steady state - Entry speed 30 mile/h - coast-by

A coast-by test was conducted for each vehicle to assess the contribution of tire and air flow noise (i.e. the total rolling noise). The engine was cut and the clutch pedal depressed at a sufficient distance before the zone entry to ensure the engine had stopped.

3.3.2 Interior Noise Tests

Interior noise levels were measured at the driver's ear position using a B & K Precision Sound Level Meter (Type 2203) for two steady state cruise conditions (top gear) of 30 mile/h and 50 mile/h. These tests were carried out on a local freeway with a sealed tarmac surface in good repair. Measurements were made in both directions and a mean level taken, to allow for wind effects (although most of the tests were carried out in low wind conditions i.e. 5-10 mile/h). Interior noise levels were also measured with the vehicle stationary and the engine idling. The latter measurements were made both with the clutch engaged and disengaged.

3.3.3 Exterior Noise Tests

With the engine idling, the sound pressure level was measured at 3m from the vehicle exterior surface at the front, rear and sides. The microphone height above the ground was 1.2m. These tests were carried out in a selected rural area where the quiescent background noise rarely exceeded 40 dBA and was more typically 30 dBA. This ensured a minimum signal/noise ratio of 10 dB. The ground surface was a normal metalled road.

3.4 TEST RESULTS

In order to analyse the drive-by noise test recordings, the microphone recorded signals were played back through a calibrated X-Y plotter. The vehicle position with respect to the four noise signals was automatically obtained by the synchronising plotter start pulse signal obtained from the phototransistor position indicators. Thus seven pulses appear along the x axis of each trace, corresponding to the seven VPIs (vehicle position indicators) spaced as shown in Figure 3-2. From these traces, the noise level at any microphone could be determined with the vehicle at any point on the test zone.

The results from the interior and idle tests are quoted as direct readings taken from the Precision Sound Level Meter.

The drive-by and interior/idle test results are presented as follows and are discussed in Section 3-5.

The results of the corresponding Saab and Peugeot tests are also included for the sake of comparisons. In all the tables and bar charts the vehicles are listed in order of ascending power/weight ratio.

3.4.1 Drive-by Tests

The results of the drive-by and coast-by tests are given in tabular form in Table 3-3. For a given test, values for the left and right sides of the vehicle are shown and are maximum levels at microphone 2 position (see Figure 3-2). For a given side, the value is a mean of two representative runs. Note that the results from the corresponding Saab and Peugeot tests have also been included for comparison. For each vehicle and each drive-by test, one representative trace of the four microphone signals is shown in Figures 3-3 - 3-62 (see list of figures for identification). The trace for the noisier side of the vehicle is shown in each case.

The results are also shown in bar chart form in Figures 3-63 - 3-65. The result for the noisier side of the vehicle is shown in each case, taken from Table 3-3.

From the 30 mile/h, 2nd gear steady state test results, polar noise graphs have been constructed. This was possible by considering the noise level at each microphone with the vehicle opposite each VPI. Thus as the vehicle proceeds through the 20m zone, so the angle between the car longitudinal axis and each microphone varies and from these angles a large part of the car polar noise radiation pattern can be mapped (the exceptions being the extreme front and rear noise paths). The sound pressure level at each microphone and at each VPI position was then corrected to 7.5m by assuming inverse square law to apply to the sound propogation fall-off rate (i.e. 6 dB per doubling of distance). Only the front three microphone signals were used due to the background noise influence on microphone 4 at the zone extremes.

These polar plots are shown for each vehicle in Figures 3-66 - 3-77.

The effect of vehicle weight on rolling noise is shown in Figure 3-78. The vehicle weight is the curb weight (from Table 3-1) and the sound pressure level is taken from an average of the left and right side values given in Table 3-3.

3.4.2 Interior Noise and Exterior Idle Noise Tests

The results of the interior noise tests at idle, 30 mile/h and 50 mile/h are shown in Table 3-4 together with the exterior idle results. Figure 3-79 shows the interior noise test results in bar chart form. Figure 3-80 compares the exterior idle results for each vehicle, as individual levels for the four measurements on each car (left, right, front and rear) and as average levels of all four sides.

3.5 DISCUSSION OF RESULTS

The typical European car is impossible to define and as would be expected, each car's noise characteristics are as diverse as its performance, economy, handling and majority of other properties. Also certain driving conditions may reflect particularly high noise levels in an otherwise quiet car; for example, the Jaguar XJ6 proved on most tests to rank as the quietest of the vehicles tested but the extreme 'Max ISO' test resulted in noise levels higher than six of the other vehicles over the same test. The Cortina showed similar tendencies in that for most normal driving conditions it would rank as relatively quiet in comparison with the other vehicles but displayed excessive noise characteristics (again by comparison) at the extreme test conditions of high engine speed. On the other hand there were cars which ranked as 'noisy' irrespective of the test type (e.g. the Peugeot). These and other points are discussed in detail below.

Considering first the standard ISO drive-by test used by the EEC for regulatory purposes, the 1977 limit for passenger cars was 82dBA, to be reduced to 80 dBA in 1980. All twelve vehicles would pass this test for the 82 dBA limit, but the Alpine S, Volvo, Peugeot and Dolomite Sprint, as tested, would have failed the 80 dBA limit. Taking the mean ISO test levels for all vehicles tested and averaging these, gives an overall figure of 78.9 dBA with a standard deviation of 1.9 dBA. The extreme scatter around this mean is +2.7dBA -3.2dBA. The Fiesta and Saab fall very close to this mean. The extremes are the Jaguar XJ6 being 75.7dBA (mean of both sides) and the Dolomite Sprint at 81.6dBA (mean of both sides). The average ISO level for each car is shown in Figure 3-81 where the cars have been arranged in order of increasing ISO test results. This clearly indicates the relative magnitudes of the levels in that the Jaguar and Chevette are significantly quieter than the mean, half of the sample of cars fall within a span of approximately 1dBA (Cortina, Renault 4, Opel 2100D and T/C version, Saab and Fiesta) and the remaining four cars fall into a further level on average some 2½dBA above the previous level. On the whole, the broad band of vehicles representing the 'middle' level are far more representative of the average European family saloons than the luxury class Jaguar and the high preformance Dolomite Sprint at the extremes. Both of these cars were included, however, partly to display extremes and partly because of one of the criteria for vehicle selection was power/weight ratio.

It is interesting to examine the remaining four drive-by tests (excluding the coast-by results which will be dealt with later) and compare the results of these tests from vehicle to vehicle on a ranking basis and in comparison with the ISO test. Figure 3-81 shows the results of all these drive-by tests. The two tests involving extreme engine speeds ('Max ISO' and 10 mile/h, 1st gear max. accel.) show that to try to establish general trends would be meaningless. It might be expected that a largely 'quiet' car like the Jaguar would rank as relatively quiet for all tests but this is not the case for the 'max ISO' condition where the difference from the standard 'ISO' test was almost 8 dBA (compared with only 2dBA for the Renault). The Cortina also appears worse during these two extreme tests but ranks as 3rd quietest on an ISO test. The Alpine S, Volvo and Peugeot, however, displayed relatively high noise levels during the ISO test and again during the two extreme engine speed tests.

The three diesel vehicles were particularly noisy (relative to the other vehicles) during the steady state 30 mile/h, 2nd gear test and again for the 30 mile/h top gear test. For this latter test the high rolling noise of the Jaguar largely accounts for its relatively high ranking, and the relatively high Saab level is attributed to the exhaust noise, being a critical function of certain engine speeds.

According to the individual test, therefore, certain cars would be more penalized than others and the question of a representative drive-by test procedure is immediately raised. It is not within the scope of this report to debate the objectivity of test procedures in detail but the following comments are relevant. If a drive-by test involving the engine running at rated speed is used as a criterion for noise evaluation (e.g. the ASA STD 3-1975 test) then this will unfairly penalize certain vehicles which probably over the vast majority of operating conditions may otherwise have been of below average noise level (e.g. the Jaguar and Cortina). If one ignores these extreme cases, however, then on the whole it would appear that the ISO test gives a reasonable indication of the overall exterior noise level of the vehicle. Figure 3-82 compares the ISO levels with the logarithmic mean of all the other drive-by tests for each vehicle. Apart from the extremes previously mentioned, this average follows the ISO levels very closely and ranks the vehicles on an exterior noise basis in precisely the same order as given by the ISO levels.

Because of the diversity of the characteristics of each vehicle there was not expected to be any specific correlation between drive-by noise level and power/weight ratio and this has been borne out by the test results. The two extremes of the ISO ranking, the Jaguar and the Dolomite Sprint are the two highest power/weight ratio cars selected. The Saab and Fiesta gave virtually identical ISO tests results yet their power/weight ratios differed by 60 percent. Clearly the very large variety of other variables far outweighs any significance of power/weight effects, although for a given vehicle under controlled conditions there is a small power/weight ratio influence (as was shown in the Saab power/weight ratio tests, DP 77/1158). A general trend, however, based on a broad categorization of the twelve cars is presented and discussed later.

It could be argued that the Dolomite Sprint may have produced above-average noise levels during an ISO test because of its superior performance resulting in higher vehicle and engine speeds in the zone. On the other hand, having a fairly high second gear ratio (equivalent to 8.9 mile/h per 1000 rev/min) would tend to compensate somewhat for this. It was nevertheless from subjective observations, considered to be particularly noisy engine as the 'Max ISO' test showed and was not attributable just to engine speed. The Fiesta with an engine rated at 6000 rev/min gave a maximum level of 84.7 dBA druing the 'Max ISO' test compared with 86.5 from the Dolomite Sprint at 5700 rev/min. The Saab with a similar size engine to the Sprint and rated at 5500 rev/min gave a 'Max ISO' level of 84.1.

Figure 3-78 shows the maximum coast-by noise for each vehicle plotted against vehicle curb weight. Again, the diversity between vehicles must be considered but here a trend is easier to detect, largely because the other variables (tire size, tire pattern, aerodynamic shape of the vehicle) have a less significant noise influence than the influence of the weight of the vehicle on the tires, and thence on the road surfaces. Apart from the Dolomite Sprint (which, it could be argued, had larger than average width tires for the size of car) a relationship:

$$\text{Max SPL (dBA)} = 10.7 \log W + 32$$

(where W = vehicle curb weight in lbs)

gives a prediction accuracy of better than $\pm$ 1 dBA for the cars tested. The relative significance of rolling noise on the overall noise level during, say, an ISO test is minimal, however, being typically 10-12 dBA below.

So far, the drive-by tests have been discussed only on the basis of the maximum levels recorded during each test. Under normal test requirements this is the only data available, but with a four-microphone array, a position indicating system and a means of recording all the signals, a deeper analysis of the events taking place over the 20m zone is made possible.

Figures 3-3 - 3-62 show the noise history of the vehicle over the 20m zone at each microphone. From these traces, the maximum levels at any microphone may be determined or the instantaneous levels at any position in the zone, by reference to the vehicle position indicator pulses. The directionality of the car noise may be readily determined both visually and by construction of polar noise plots. Visual examination of the symmetry of the three traces from microphones 1, 2 and 3 gives a qualitative indication of the noise directionality. For example, if an omni-directional noise source is moved through the site a symmetrical trace is obtained for microphones 1, 2 and 3. For a directional noise source, however, a measure of the directionality is obtained by reference to the sound pressure level at microphone 2 at the beginning and end of the zone for a steady state drive-by condition. This is clearly shown in Figure 3-36 shows the difference in microphone 2 levels between exit and entry is some 3dBA. Also the deviation from omni-directional source symmetry is apparent from comparison of the relative levels of microphones 1, 2 and 3 during the first half and the second half of th 20m zone.

The polar plots, constructed from the 30 mile/h, 2nd gear steady state tests give a quantitive indication of the directional nature of the noise source. The noise contour is reasonably circular in shape for most of the cars tested, particularly when considering the accuracy of the plots obtained (approximately ± 1 dBA). In certain cases the deviation from the circular is seen where, for example, the vehicle has particularly significant exhaust noise (Saab, left hand side), or the engine is noisy to the front of the vehicle, so tending to 'flatten' the noise contour in this area as was the case in the majority of the cars tested (Renault 4, Opel 2100D, Peugeot 504 GLD, Alpine S, Volvo, Saab, Jaguar). The general deviation from the circular towards the rear of the car is because a car is not a point source and the reference point chosen was the center of the axis through the side facing spotlights.

Comparing the naturally aspirated Opel 2100D to the prototype turbocharged version, for a given engine speed condition (i.e. the steady state tests) there is very close agreement between the results from the two cars which would be expected for such light load conditions (i.e. negligible boost from the turbocharger). For the accelerating conditions there is still only marginal differences, and this being largely because the improved performance of the turbocharged Opel is resulting in the engine reaching a higher speed in the zone (notable during the 10 mile/h, 1st gear, max. accel. test). For the 'Max ISO' test, the entry speed for the turbocharged Opel was 35 mile/h, and was 38 mile/h for the standard car; both entry speeds permitting rated engine speed to be reached at the zone exit. For this test, a maximum microphone 2 level of 81.1 was recorded for the standard Opel and 80.8 for the turbocharged version, the discrepancy being insignificant in the light of drive-by repeatability. Thus, turbocharging did not significantly affect the drive-by noise levels as was to be expected from such IDI diesel engines where the noise characteristics (at the higher engine speed range) are generally controlled more by mechanical than combustion excitation.

For the purpose of generalization, it is possible to broadly categorize the twelve cars into three groups: Small (seating capacity of 4, engine under 80 in^3, curb weight under 1800 lb), Medium (seating capacity of 4-5, engine 85-120 in^3, curb weight around 2000 lb) and High-Performance Luxury (seating capacity 4-5, engine over 120 in^3, curb weight 2000-4000 lb). Obviously there will be 'grey' areas when classifying the cars under these broad headings but a general trend in interior and exterior noise characteristics is apparent. Under the "Small" category are the Renault, Fiesta and Chevette cars. The Volvo, Jaguar and Dolomite Sprint classify as 'High-Performance Luxury' saloons. The remainder have been grouped in the middle category, with no differentiation between type of powerplant; the vehicles have all been regarded as means of transportation only, for this purpose. The following table summarizes the ISO and interior noise level of each category. The values arrived at are log means of the individual mean result for each car (levels quoted in dBA).

Category	ISO Test	Interior at 50 mile/h
Small Saloon	78.0 + 1.1 - 1.4	73.4 + 2.4 - 2.3
Medium Saloon	79.4 + 1.9 - 1.6	71.3 + 1.5 - 1.3
High Performance, Luxury Saloon	80.8 + 1.6 - 4.3	68.1 + 1.4 - 4.1

The maximum scatter above and below the means is also given, in dBA. Clearly, there is a general trend in that the ISO drive-by level increases with increasing size and performance of car and that the interior noise reduces. This does not imply a specific power/weight ratio dependence, however, as, for example, the Saab at 0.042 bhp/lb and the Peugeot at 0.022 bhp/lb are both grouped in the same category, but it does imply a general dependence on the 'type' of car. The statistical significance of basing this argument on a very small sample is recognized as being questionable, but the general trend is interesting and is also what might be broadly predicted from experience of widely ranging European passenger cars.

The measured interior noise levels show a wide variation between cars, as shown in Table 3-4, this largely being a function of class of car and the degree of sound treatment used. At 30 mile/h cruise the overall mean interior noise was 64.9 dBA (standard deviation 3.0 dBA), extremes +4.1, -7.1). At 50 mile/h cruise the corresponding figures were 70.7, 2.8, +5.1, -6.7, the higher speed tending to exaggerate further the differences between individual cars. Comparing the diesel and gasoline cars at the two cruise speeds the average diesel car interior noise is only approximately 1 dBA greater than that for the gasoline car average. At idle, however, this difference increases to more than 3 dBA.

The results of the exterior idle tests clearly indicate the high noise levels associated with diesel engine idling. The diesel car average exceeds the gasoline car average by some 6 dBA. The problem of diesel idle noise is one which is currently continuing to be examined closely, both from the aspects of measured levels and also subjective tests. It is well recognized that impulsive noise characteristics as evident in diesel idling may not necessarily be adequately assessed by an 'A'-weighted sound pressure level.

3.6 CONCLUSIONS

- The overall average drive-by noise level of the 12 cars on the ISO type test was 78.9 dBA with a standard deviation of 1.9 dBA and an extreme scatter of +2.7 dBA -3.2 dBA.

- There was no correlation between drive-by noise and power/weight ratio.

- The average interior noise at 50 mile/h cruise was 70.7 dBA with a standard deviation of 2.8 dBA, and an extreme scatter of +5.1 dBA, -6.7 dBA. The wide scatter reflects the large variation in sound proofing used in different cars rather than the engine type.

- Engine idle noise was on average some 6 dBA higher for the diesel cars than the gasoline cars, this being due to the particular idle noise characteristics of the light duty diesel engine.

- Good correlation between vehicle curb weight and coast-by noise was seen and a simple empirical prediction formula obtained giving a prediction accuracy of better than ± 1 dBA.

TABLE 3-1. ADDITIONAL VEHICLE NOISE TESTS
BRIEF DESCRIPTION OF VEHICLES

Vehicle	Engine Capacity ℓ	Engine Capacity ins^3	Engine * DIN Power bhp (P)	Engine Speed at Max. Power rev/min	Kerb weight lb(W)	Nominal Power/wt ratio P/W bhp/lb	Approx. mileage at time of test
RENAULT 4	0.845	51.6	34	5000	1532	0.022	6000
OPEL 2100D	2.068	126	60	4400	2723	0.022	2000
PEUGEOT 504 GLD	2.304	141	70	4500	2866	0.024	3000
FORD FIESTA	0.957	58	40	6000	1543	0.026	500
OPEL 2100 T/C	2.068	126	84	4400	2723	0.031	8000
CORTINA 1600	1.593	97.2	72	5500	2260	0.032	12000
CHEVETTE GL	1.256	76.6	59	5600	1863	0.032	16000
ALPINE S	1.442	88.0	85	5600	2359	0.036	6000
VOLVO 244 GL	2.127	129	123	5500	2922	0.042	1500
SAAB 99 GL	1.985	121	100	5500	2650	0.038	3000
JAGUAR XJ6	4.235	258	180	4500	3938	0.046	16000
DOLOMITE SPRINT	1.998	122	127	5700	2295	0.055	2000

*manufacturer's figure

All vehicles powered by gasoline engines except for the Opel 2100D, Opel 2100 T/C and Peugeot 504 which are powered by Comet V diesel engines. The Opel 2100 T/C is a turbocharged version of the Opel 2100D and is a prototype model. (The remaining vehicles are standard production models).

The SAAB and Peugeot are in 1976 California Build. The other production cars are all in standard U.K. build.

TABLE 3-2. ADDITIONAL VEHICLE NOISE TESTS
ISO AND 'MAX ISO' TEST SPEEDS

Vehicle	ISO TEST		'MAXIMUM ISO TEST'			
	Vehicle speed at ¾ rated speed mile/h	Actual Entry Speed mile/h	ENTRY		EXIT	
			Vehicle Speed mile/h	Engine Speed rev/min	Vehicle Speed mile/h	Engine Speed rev/min
RENAULT 4	25	25	30	4500	33	5000
OPEL 2100D	28	28	35	4050	38	4400
PEUGEOT 504 GLD	28	28	33	3950	37	4500
FORD FIESTA	32	31	39	5550	42	6000
OPEL 2100D T/C	28	28	35	4050	38	4400
CORTINA 1600	36	31	44	5150	47	5500
VAUXHALL CHEVETTE	30	30	36	5050	40	5600
ALPINE 'S'	34	31	40	5000	45	5600
VOLVO 244 GL	39	31	43	4550	52	5500
SAAB 99 GL	38	31	42	4500	51	5500
JAGUAR XJ6	52	31	40	4000	45	4500
DOLOMITE SPRINT	38	31	42	4700	51	5700

All ISO tests in 2nd gear (D2 for Jaguar XJ6).

All 'MAX ISO' tests in 2nd gear (D1 for Jaguar XJ6).

TABLE 3-3. ADDITIONAL VEHICLE NOISE TESTS DRIVE-BY TESTS MAXIMUM dBA LEVELS AT MIC. 2 POSITION (AVERAGED FROM TWO REPEATABLE RUNS)

VEHICLE	MAXIMUM ACCEL.						STEADY STATE (30 MILE/H)							
	ISO		'Max ISO'		10mph 1st		2nd gear		Top gear		coast-by		overall means*	
	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	LEFT	RIGHT	A	B
RENAULT 4	77.6	78.2	81.0	78.8	77.5	77.9	73.7	74.3	67.9	68.3	66.7	67.1	77.0	76.7
OPEL 21000	77.9	78.3	81.1	81.1	79.7	79.4	75.7	76.8	71.2	71.0	68.4	68.2	78.3	78.4
PEUGEOT 504 GLD	81.5	81.0	84.1	83.4	83.1	82.3	80.5	80.4	71.7	72.5	68.5	69.2	81.5	81.5
FORD FIESTA	79.2	78.9	83.4	83.7	81.7	82.5	72.8	72.7	68.8	68.6	65.4	65.8	80.0	80.2
OPEL 21000 T/C	78.4	78.3	80.8	80.4	81.3	80.6	76.3	76.5	71.3	70.6	68.5	68.0	78.6	78.7
CORTINA 1600	77.3	78.3	82.3	82.5	81.5	81.4	72.6	73.5	68.2	68.5	67.2	67.9	79.1	79.3
CHEVETTE GL	77.1	76.1	79.7	80.0	77.1	77.7	71.8	72.4	67.2	67.2	65.6	66.5	76.4	76.4
ALPINE S	80.5	80.3	83.6	83.7	82.9	84.1	73.6	72.9	69.9	69.4	68.6	68.0	80.8	80.9
VOLVO 244 GL	80.6	80.7	84.8	84.6	83.0	84.0	73.3	73.7	69.8	69.3	69.2	69.4	81.3	81.4
SAAB 99 GL	79.1	78.6	84.1	80.4	81.7	78.9	74.5	73.1	72.2	70.9	69.4	69.3	79.0	79.2
JAGUAR XJ6	75.9	75.5	83.2	83.8	74.9	74.8	71.8	71.2	70.9	70.5	70.4	70.3	78.0	76.5
DOLOMITE SPRINT	81.4	81.8	85.2	86.5	82.0	80.7	73.4	73.0	70.0	69.9	68.9	69.9	81.5	81.5
OVERALL MEAN	78.9	78.8	82.8	82.4	80.6	80.4	74.2	74.2	69.9	69.7	68.1	68.3	79.3	79.4
STANDARD DEVN	1.8	1.9	1.8	2.3	2.7	2.8	2.4	2.5	1.6	1.5	1.5	1.4	1.7	1.8

*A = Arithmetic mean of all tests (and LHS + RHS) except coast-by

B = As 'A' but less ISO test

TABLE 3-4. ADDITIONAL VEHICLE NOISE TESTS INTERIOR NOISE AND EXTERIOR IDLE NOISE (LEVELS IN dBA)

VEHICLE	INTERIOR MEASUREMENTS				EXTERIOR MEASUREMENTS (3m from car surface, 1.2m above road)				
	30mile/h	50mile/h	Idling Clutch Free	Idling Clutch driving	FRONT	LHS	RHS	REAR	Log. Mean exterior idle noise
RENAULT 4	69.0	75.8	44.0	44.0	48.0	47.5	47.5	46.0	47.3
OPEL 2100D	64.4	70.6	53.5	55.0	63.0	61.0	61.0	56.0	60.3
PEUGEOT 504 GLD	65.5	71.8	51.8	51.8	64.5	63.5	64.5	57.0	63.2
FIESTA	67.3	71.8	47.0	48.0	-56.0 *61.0	-53.5 *54.5	-53.5 *55.0	-54.0 *54.5	57.3*
OPEL 2100D T/C	68.0	72.1	48.2	49.0	63.5	59.0	59.0	55.0	60.2
CORTINA 1600	63.5	69.9	50.5	51.5	57.5	57.5	57.0	56.0	57.0
CHEVETTE GL	64.6	71.1	47.0	47.0	50.5	51.5	51.5	51.0	51.1
ALPINE S	66.8	72.8	53.0	54.5	-59.0	-56.0	-56.5	-54.0	56.7
VOLVO 244 GL	63.8	69.0	51.5	51.5	59.5	58.5	57.5	57.5	58.3
SAAB 99 GL	62.5	70.0	47.4	47.8	-58.5	-55.0	-55.0	-56.5	56.5
JAGUAR XJ6	57.8	64.0	41.0A	41.0A	57.0	54.0	54.5	53.5	55.0
DOLOMITE SPRINT	65.0	69.5	48.0	48.5	53.5	53.5	53.5	53.0	53.4
O/A MEAN	64.9	70.7		49.1					56.4
STANDARD DEVIATION	3.0	2.8		4.1					4.3

* Electrically driven fan on

- Electrically driven fan off

A Auto transmission in neutral

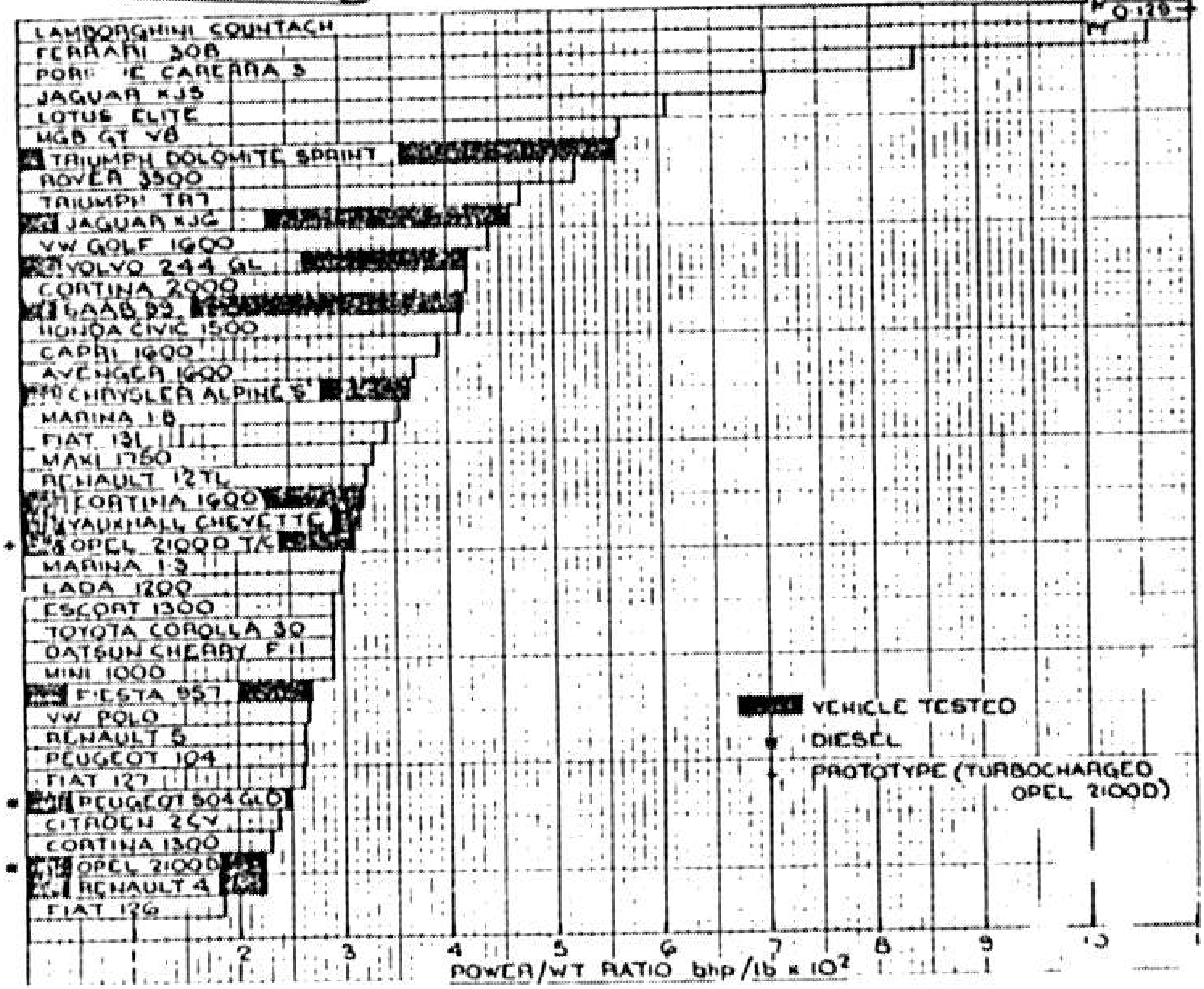


FIGURE 3-1. EUROPEAN PASSENGER CAR POWER/WEIGHT RATIOS

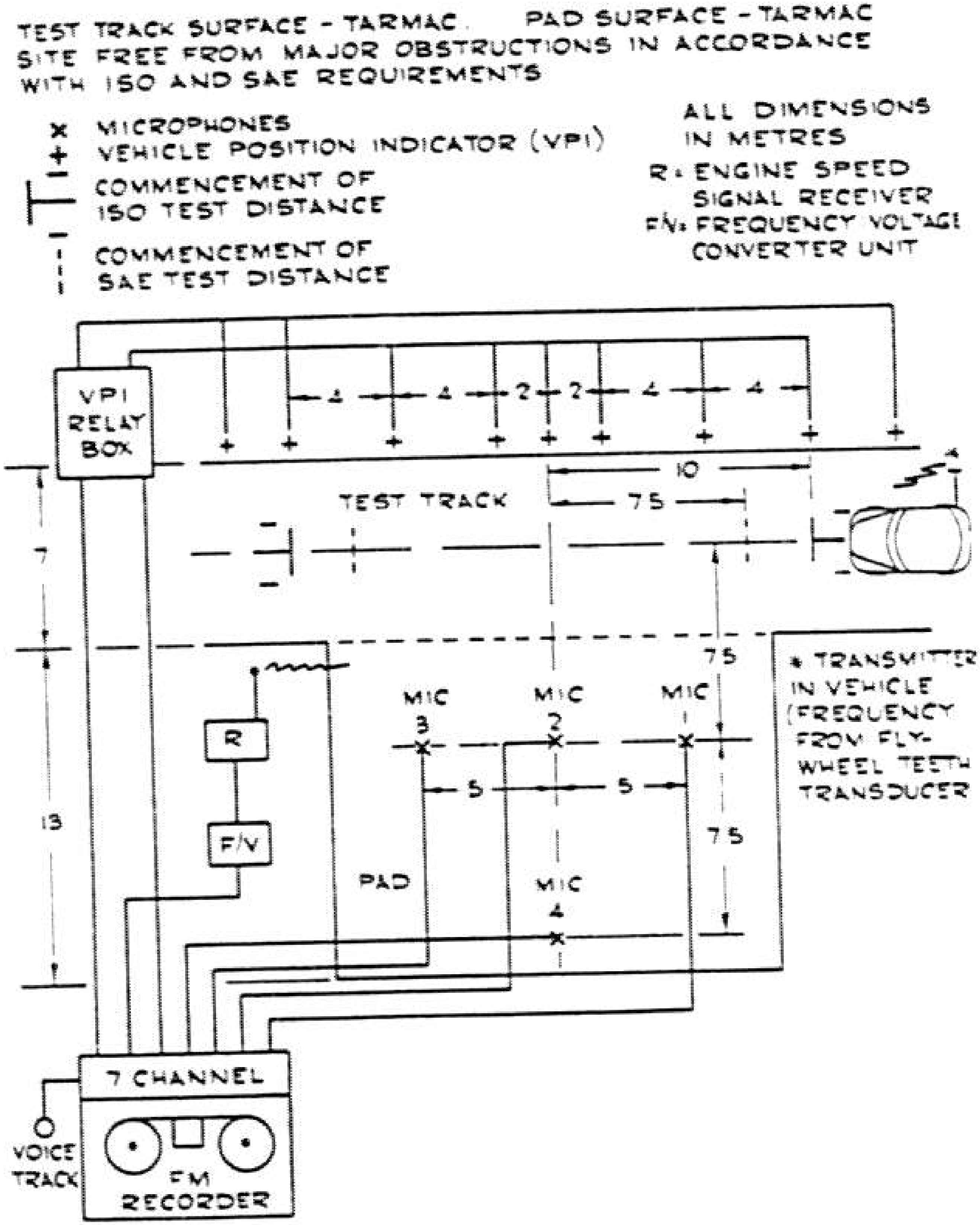


FIGURE 3-2. RICARDO DRIVE-BY NOISE TEST SITE AND SCHEMATIC LAYOUT OF INSTRUMENTATION

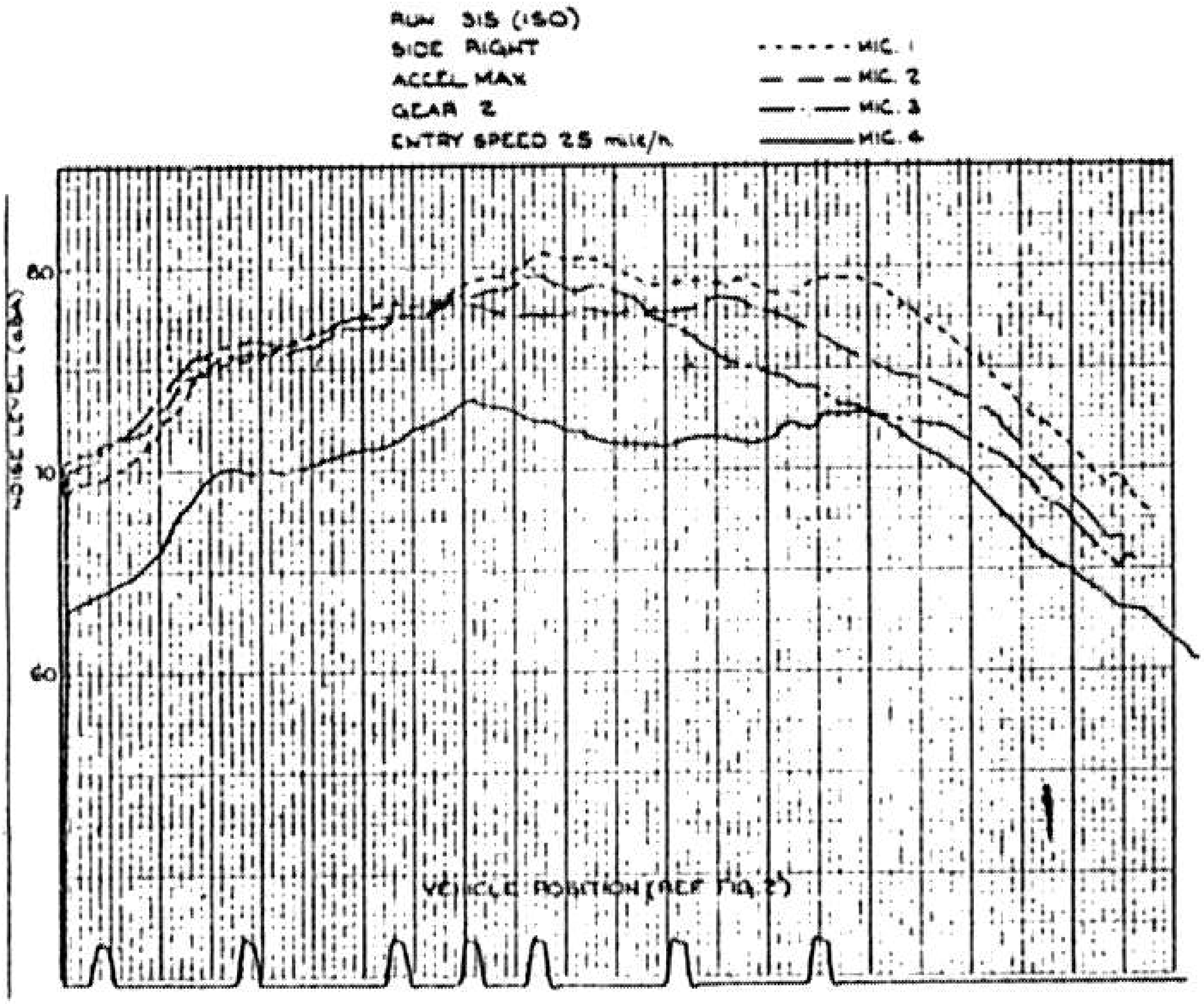


FIGURE 3-3. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - RENAULT 4

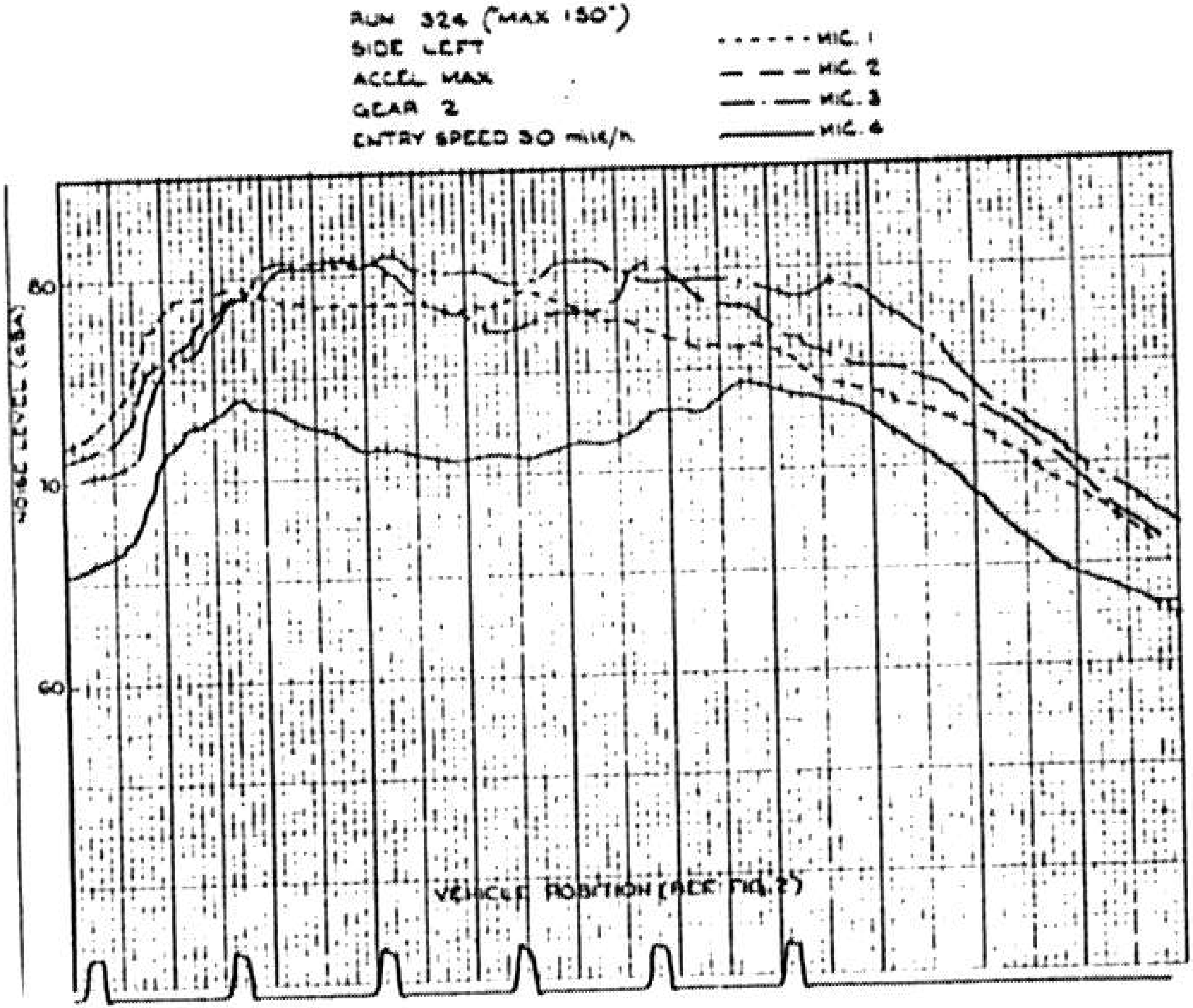


FIGURE 3-4. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - RENAULT 4

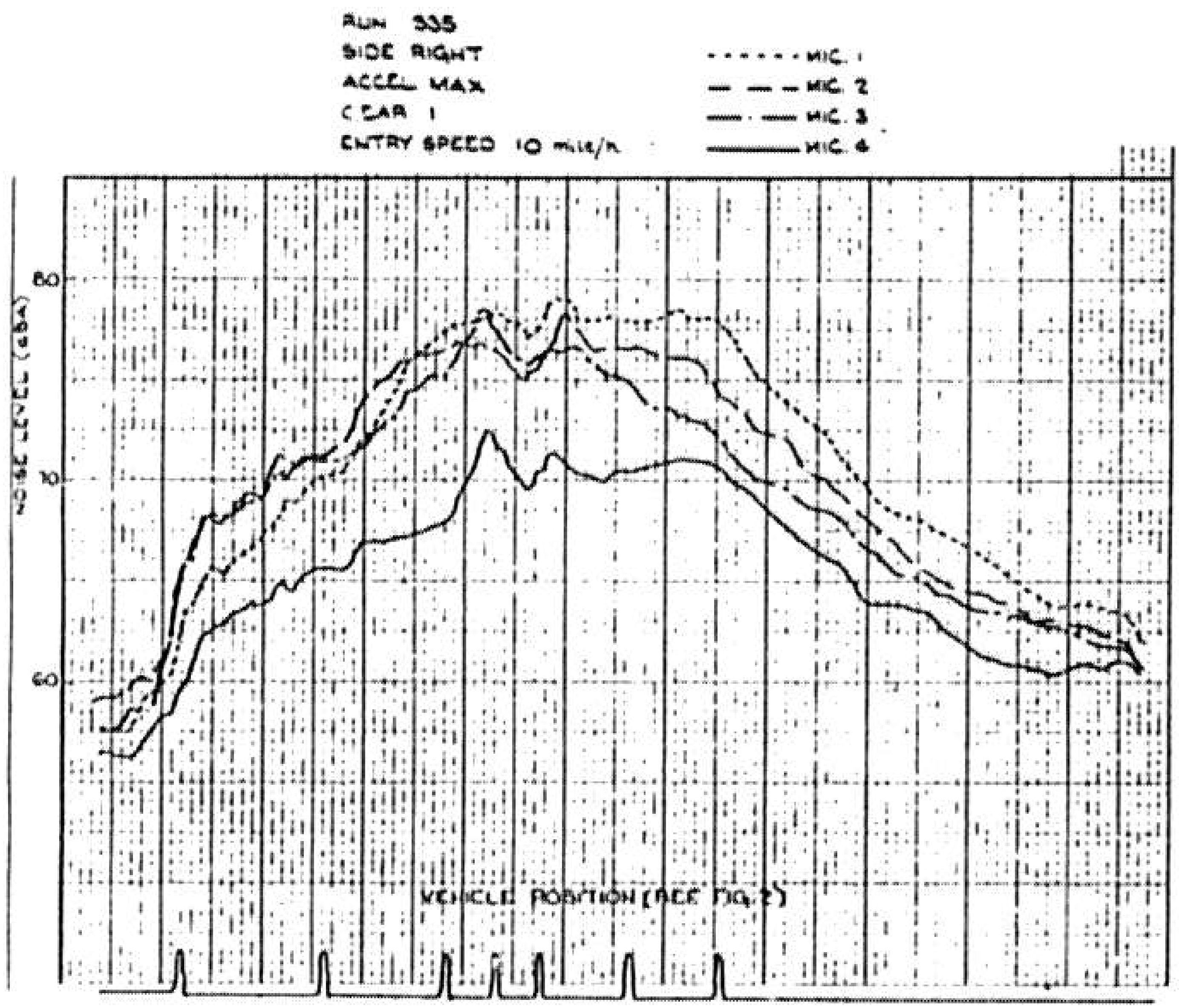


FIGURE 3-5. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - RENAULT 4

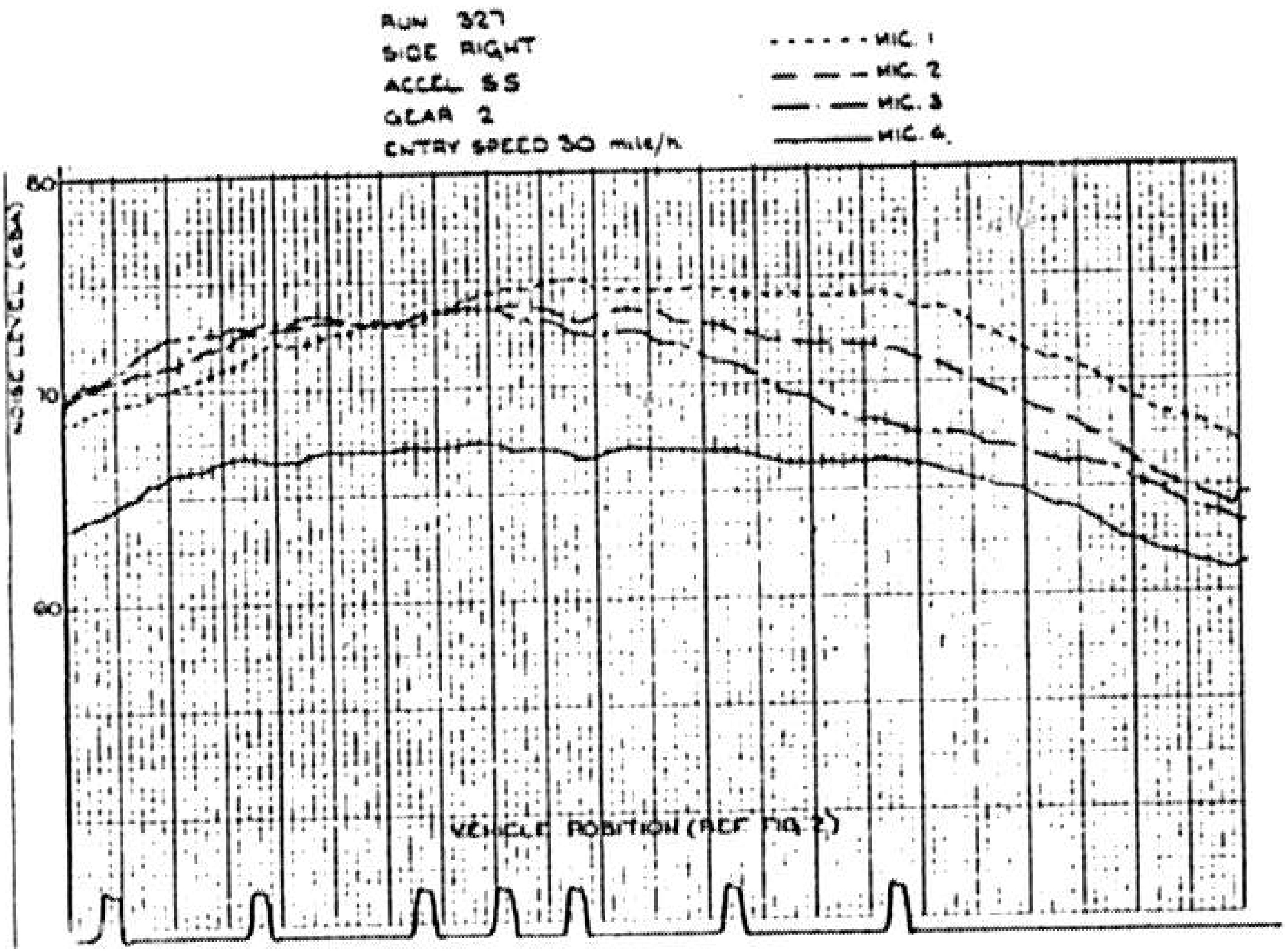


FIGURE 3-6. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - RENAULT 4

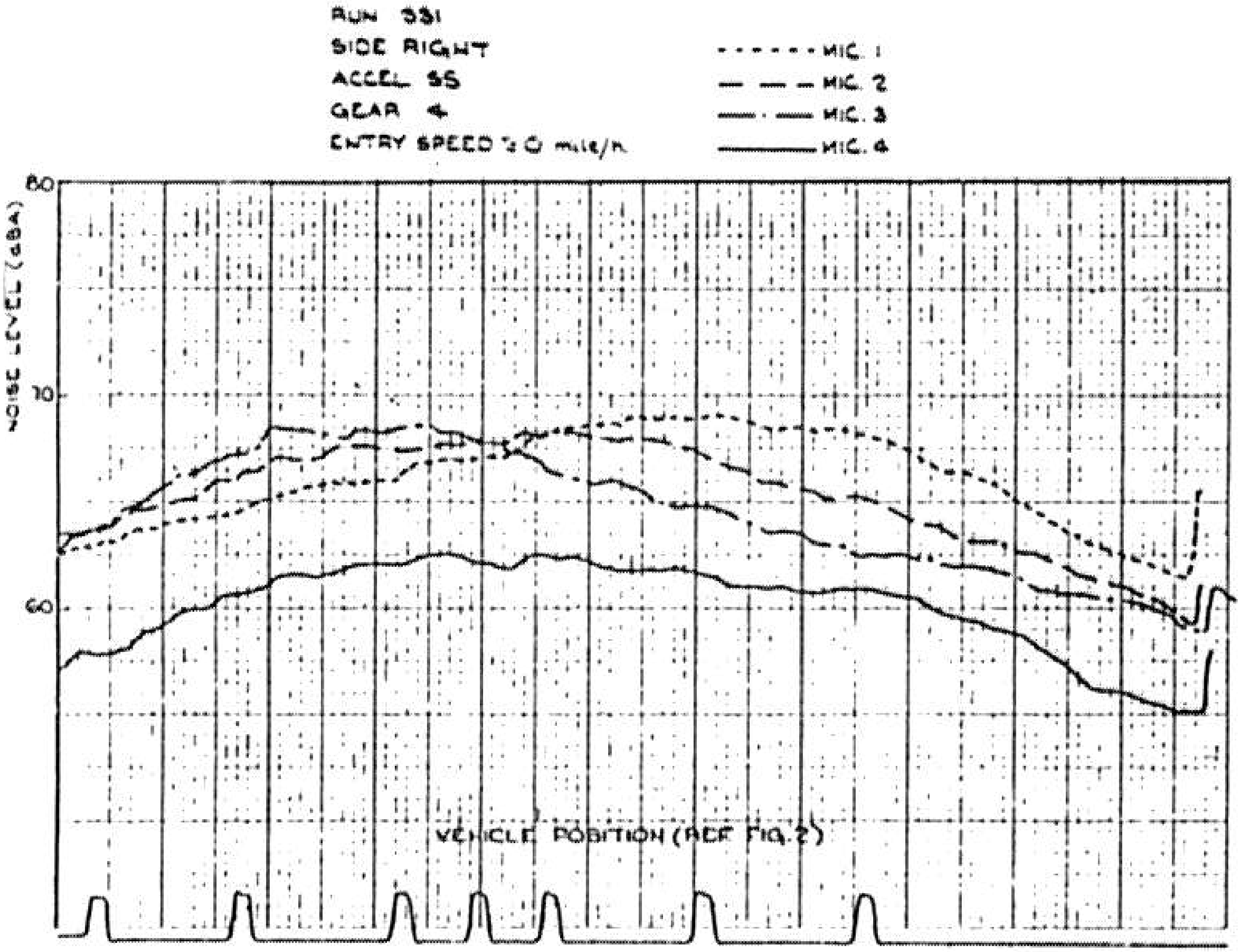


FIGURE 3-7. CALSPAN/DOT HIGH SPEED E'GINES PROJECT DRIVE-BY NOISE TRACES - RENAULT 4

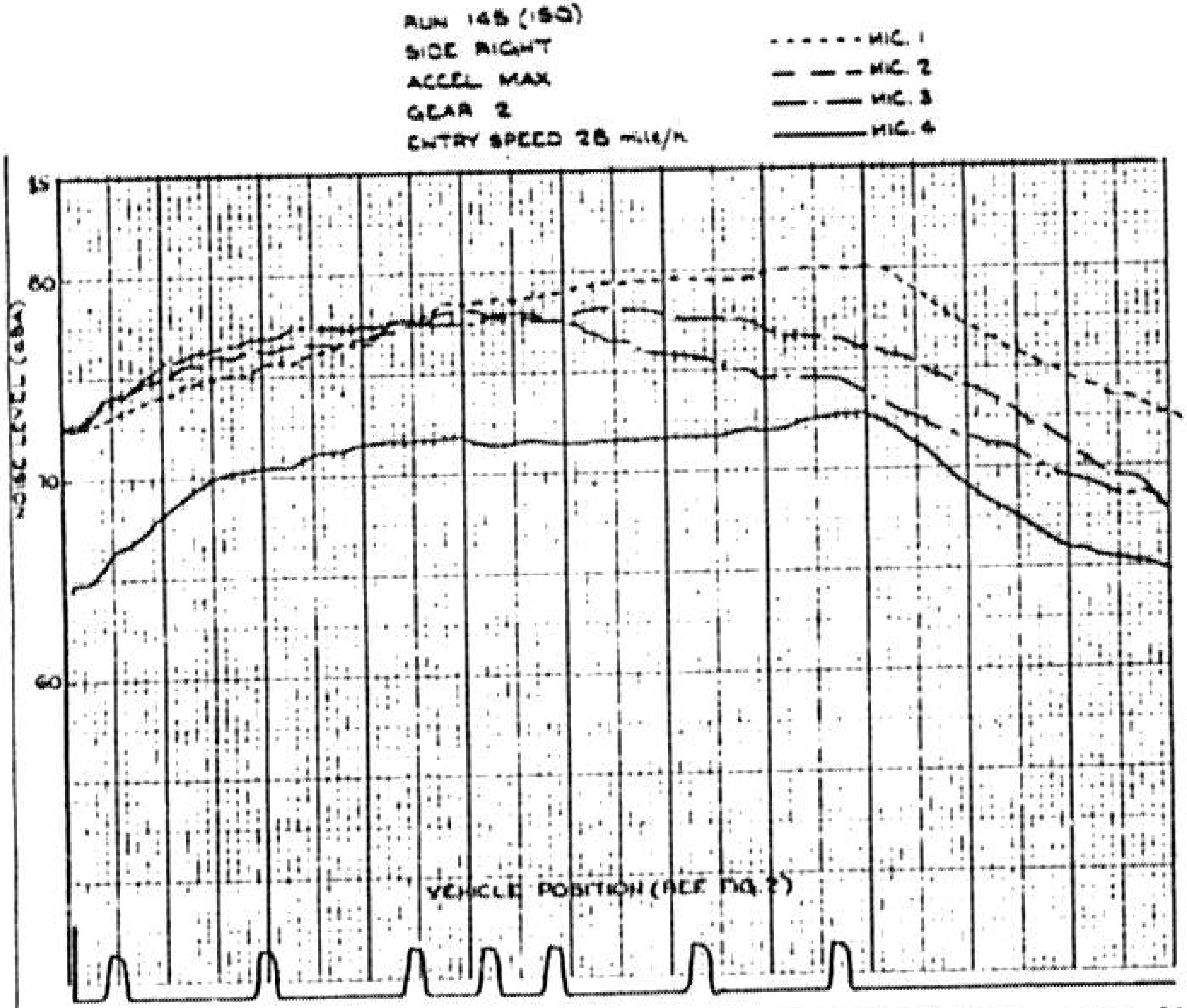


FIGURE 3-8. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - OPEL 2100D

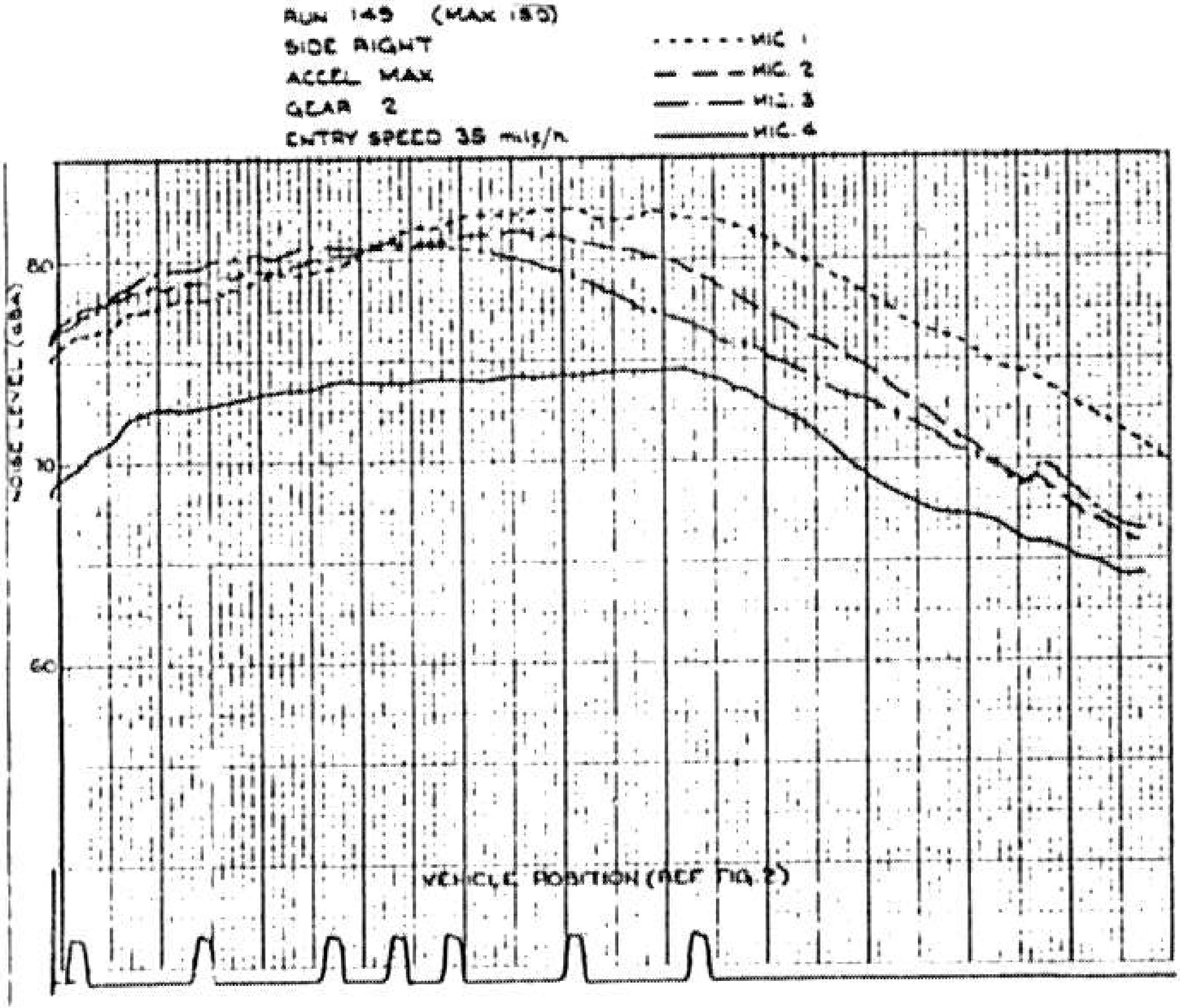


FIGURE 3-9. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - OPEL 2100D

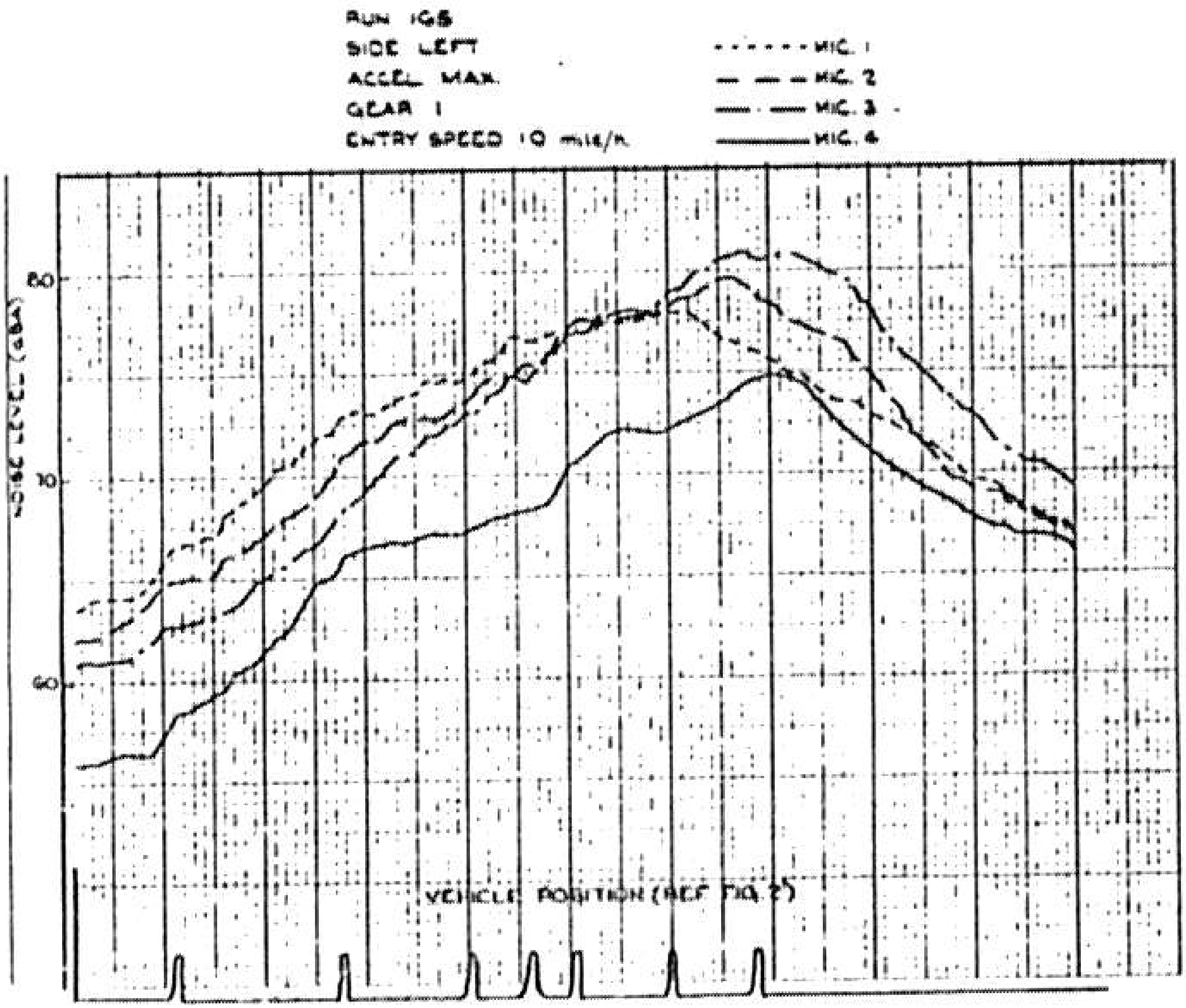


FIGURE 3-10. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - OPEL 2100D

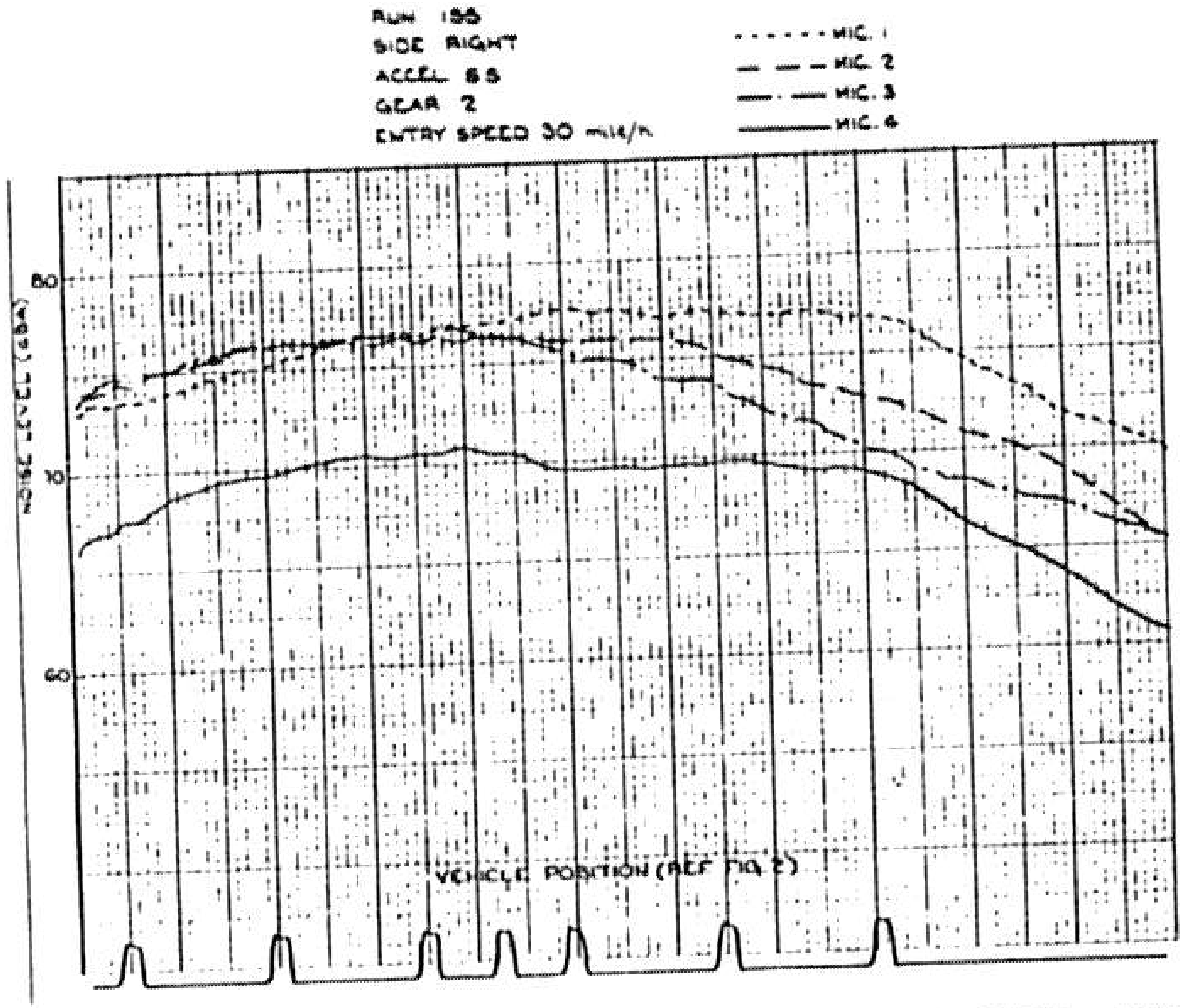


FIGURE 3-11. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - OPEL 2100D

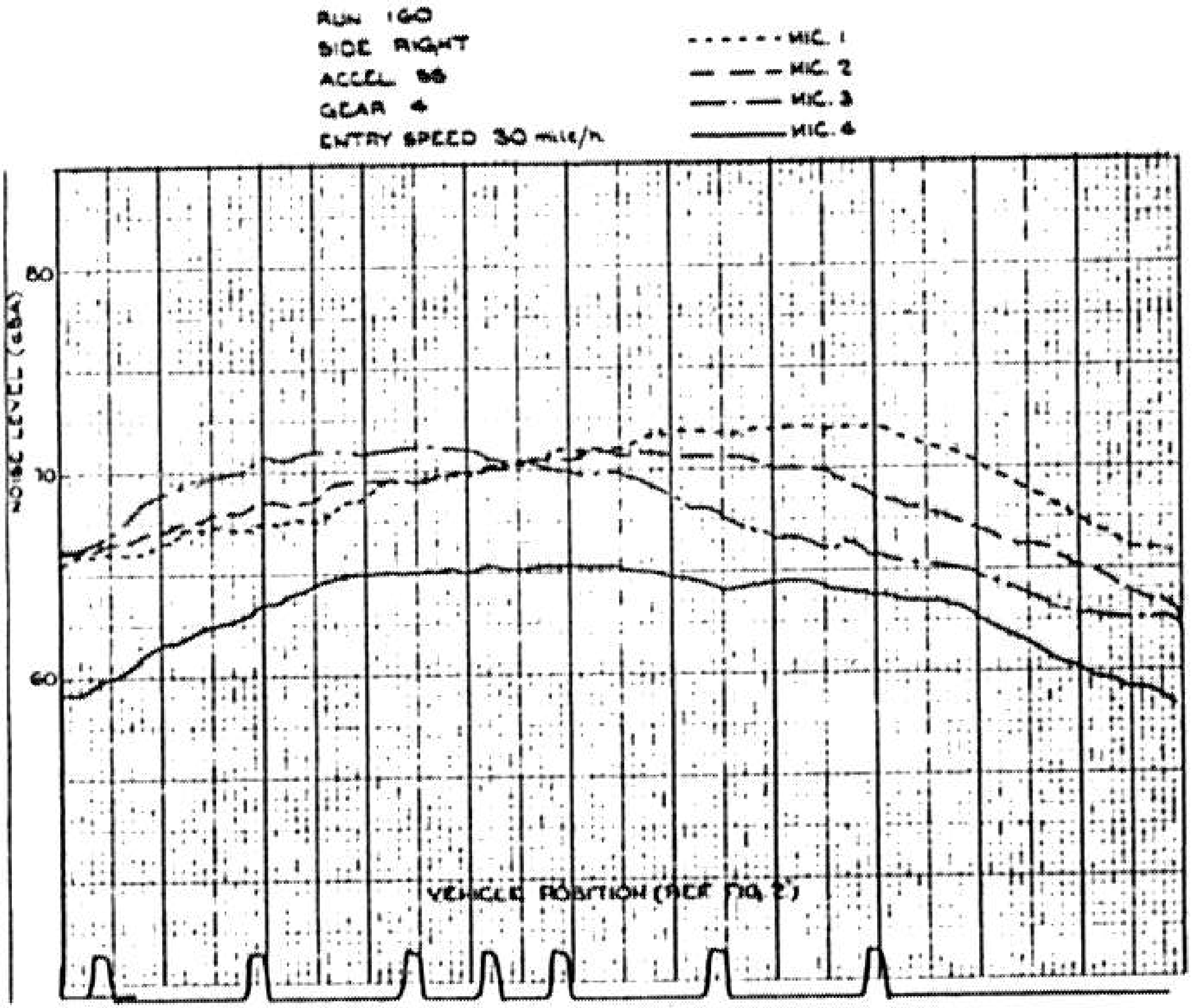


FIGURE 3-12. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - OPEL 2100D

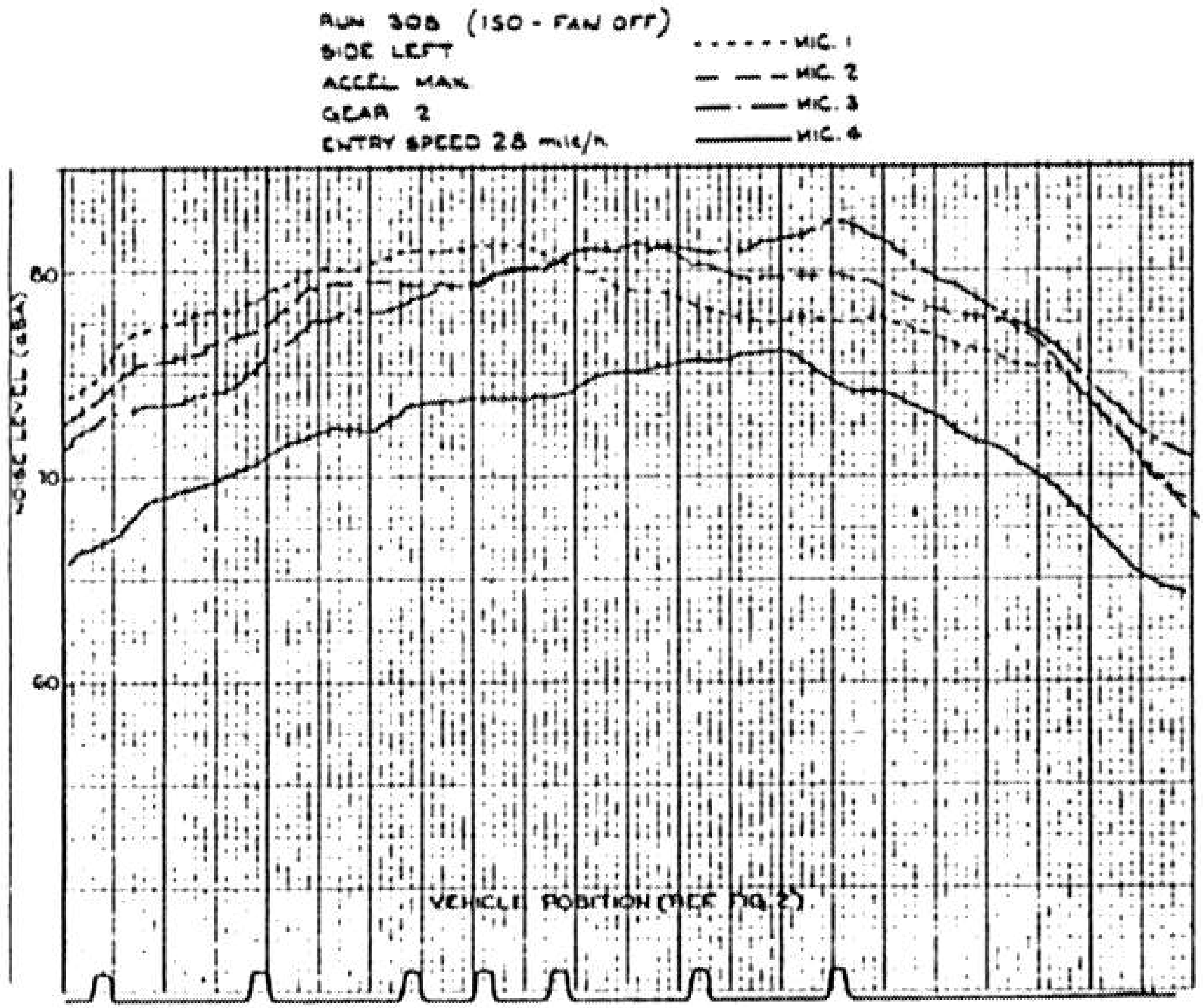


FIGURE 3-13. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - PEUGEOT 504GLD

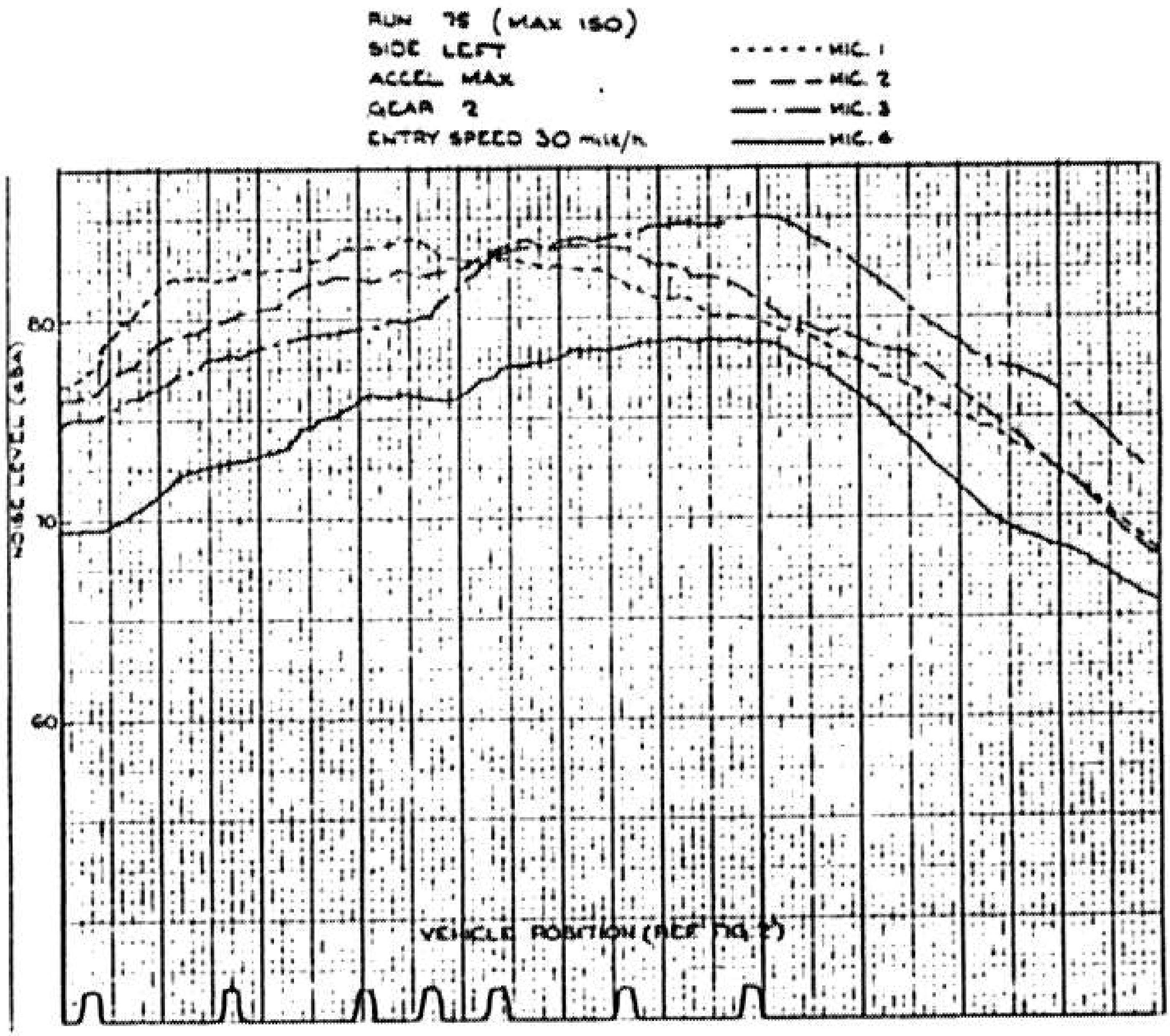


FIGURE 3-14. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - PEUGEOT 504GLD

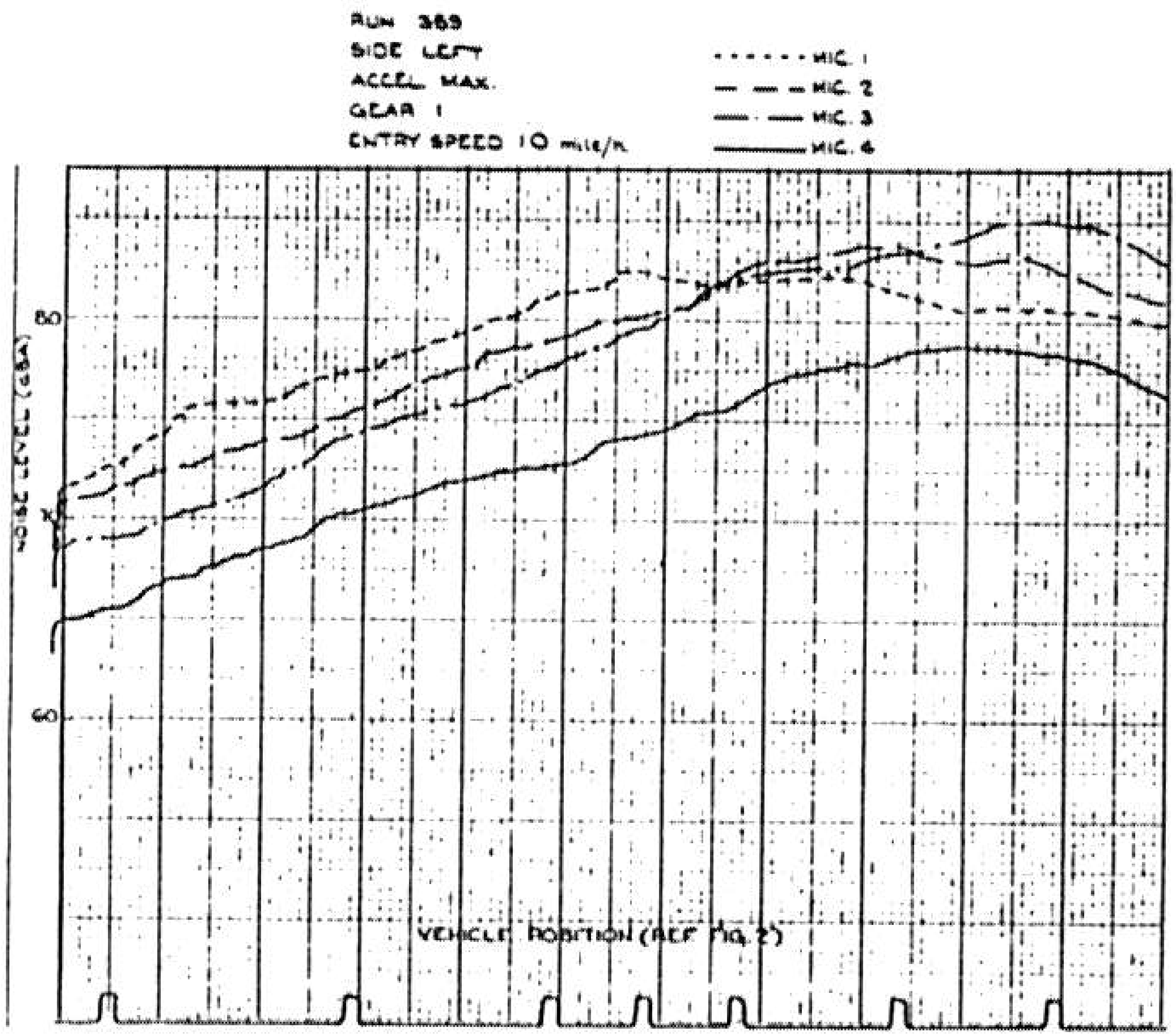


FIGURE 3-15. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - PEUGEOT 504GLD

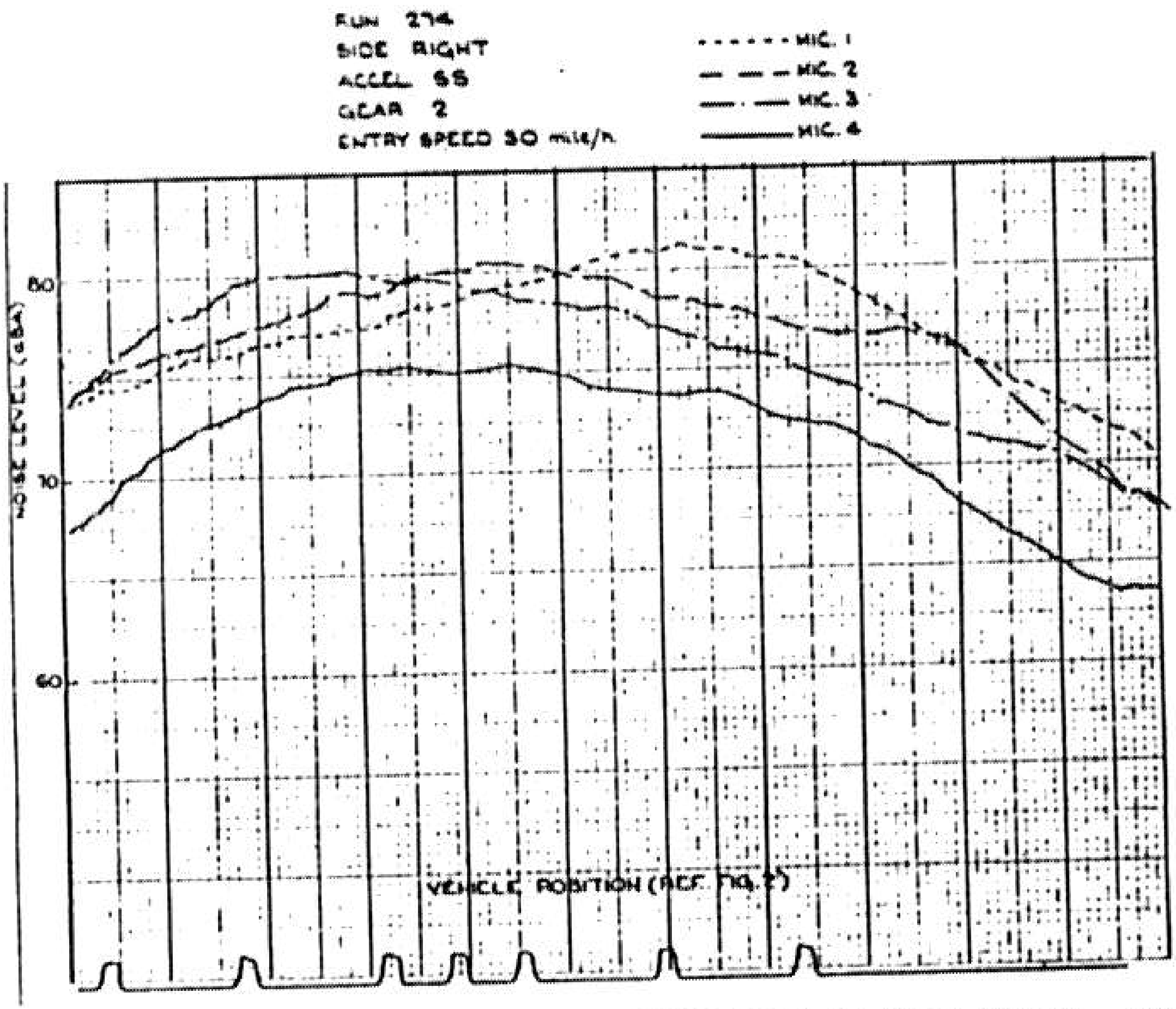


FIGURE 3-16. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - PEUGEOT 504GLD

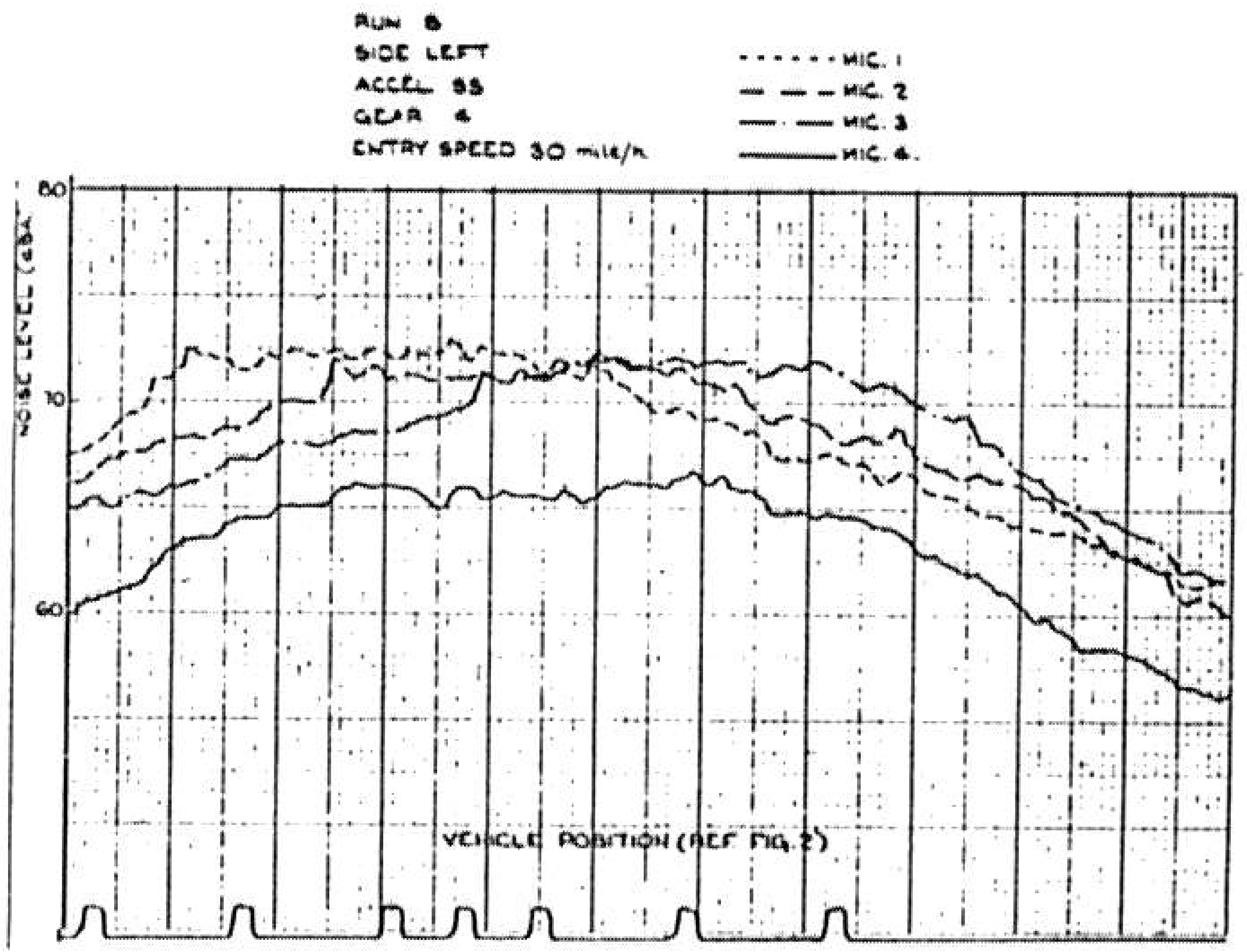


FIGURE 3-17. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - PEUGEOT 504GLD

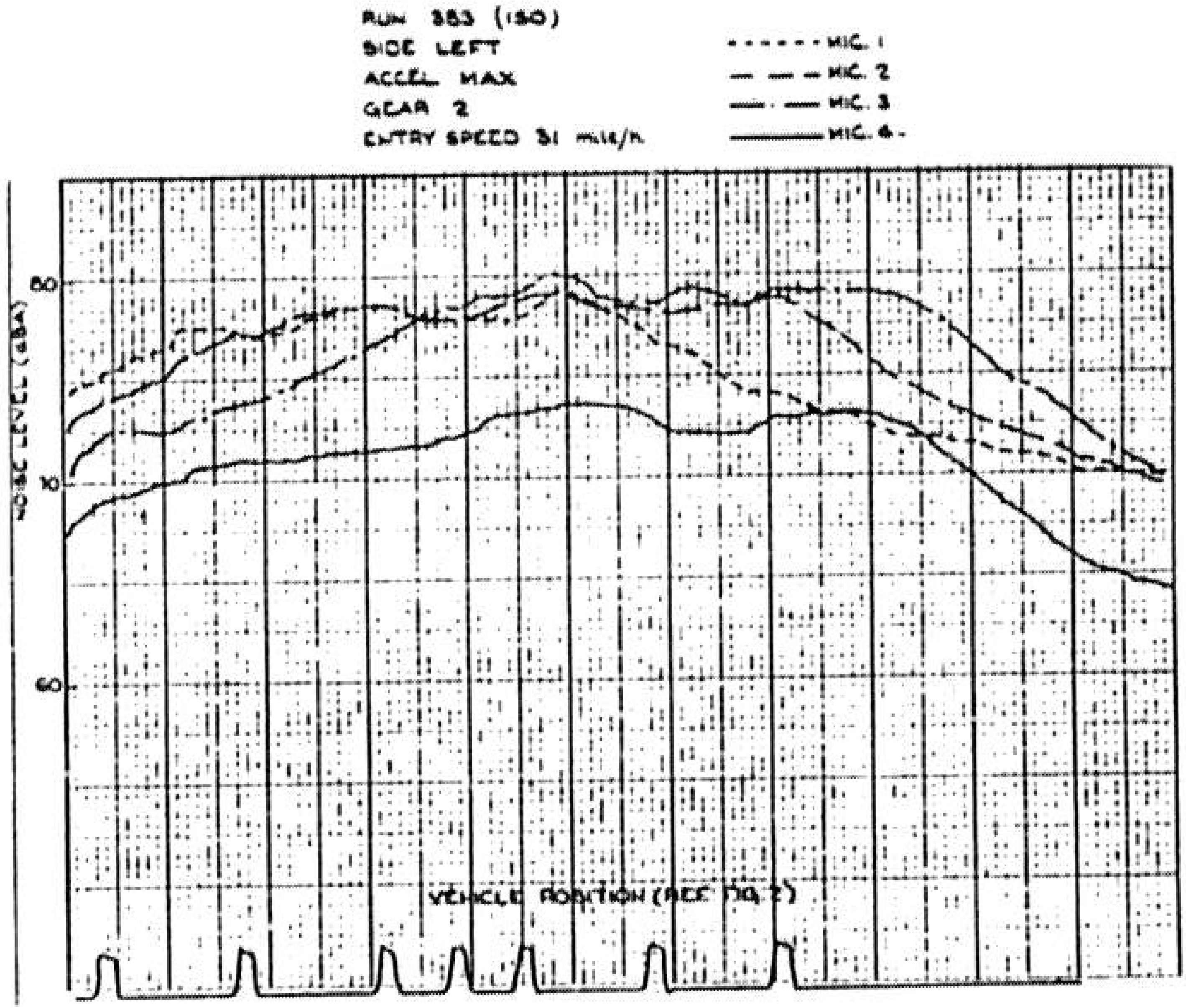


FIGURE 3-18. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - FIESTA

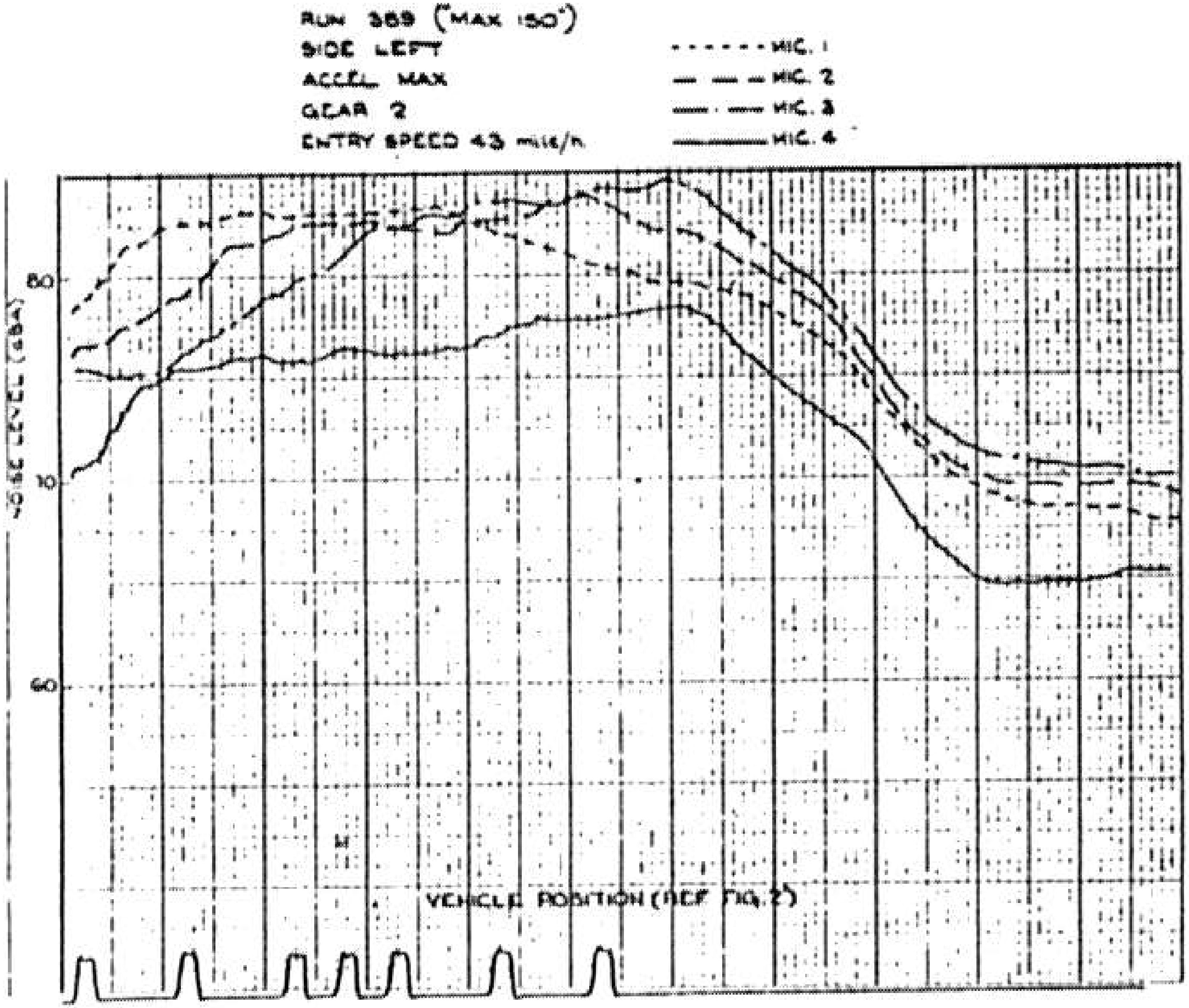


FIGURE 3-19. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - FIESTA

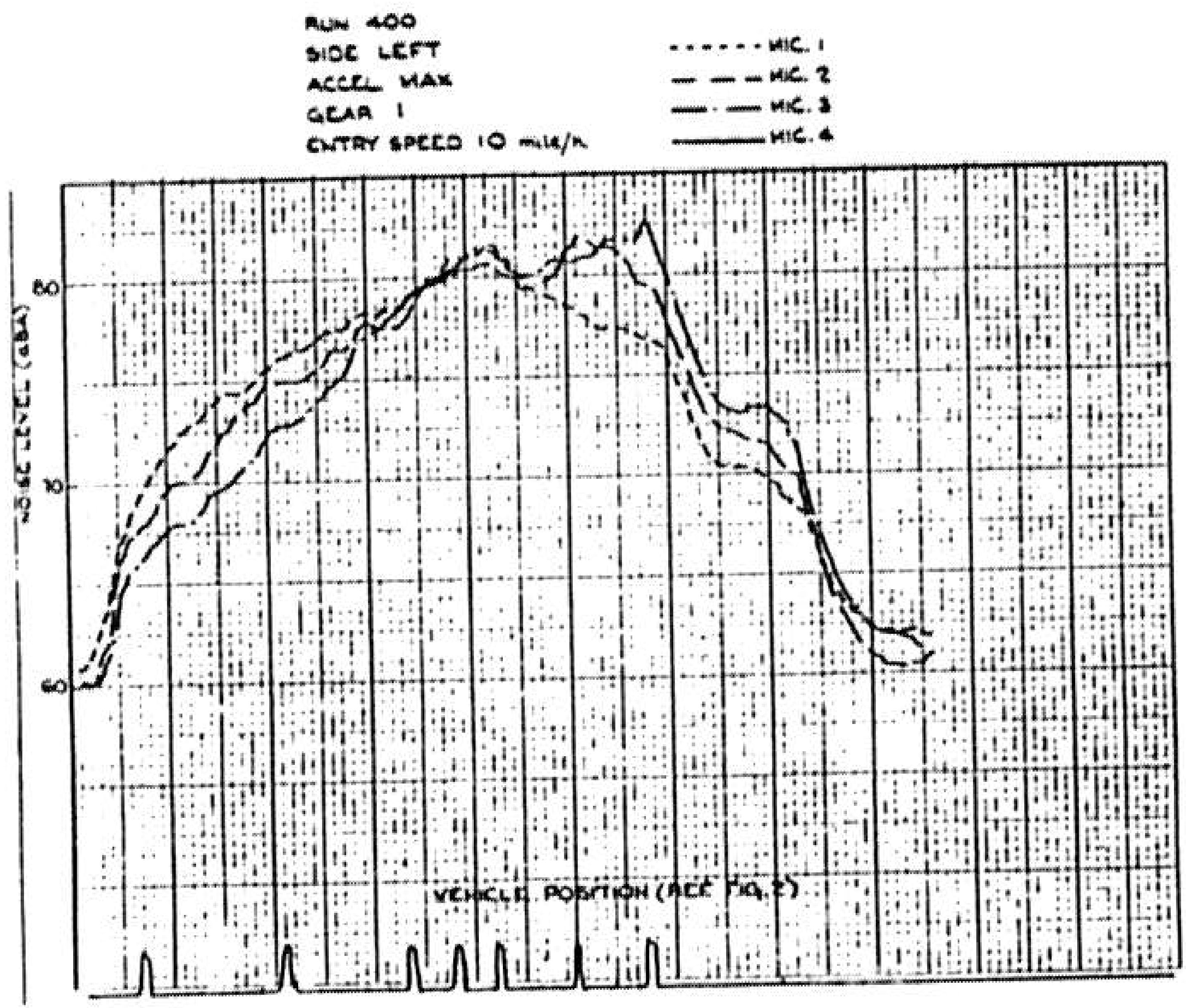


FIGURE 3-20. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - FIESTA

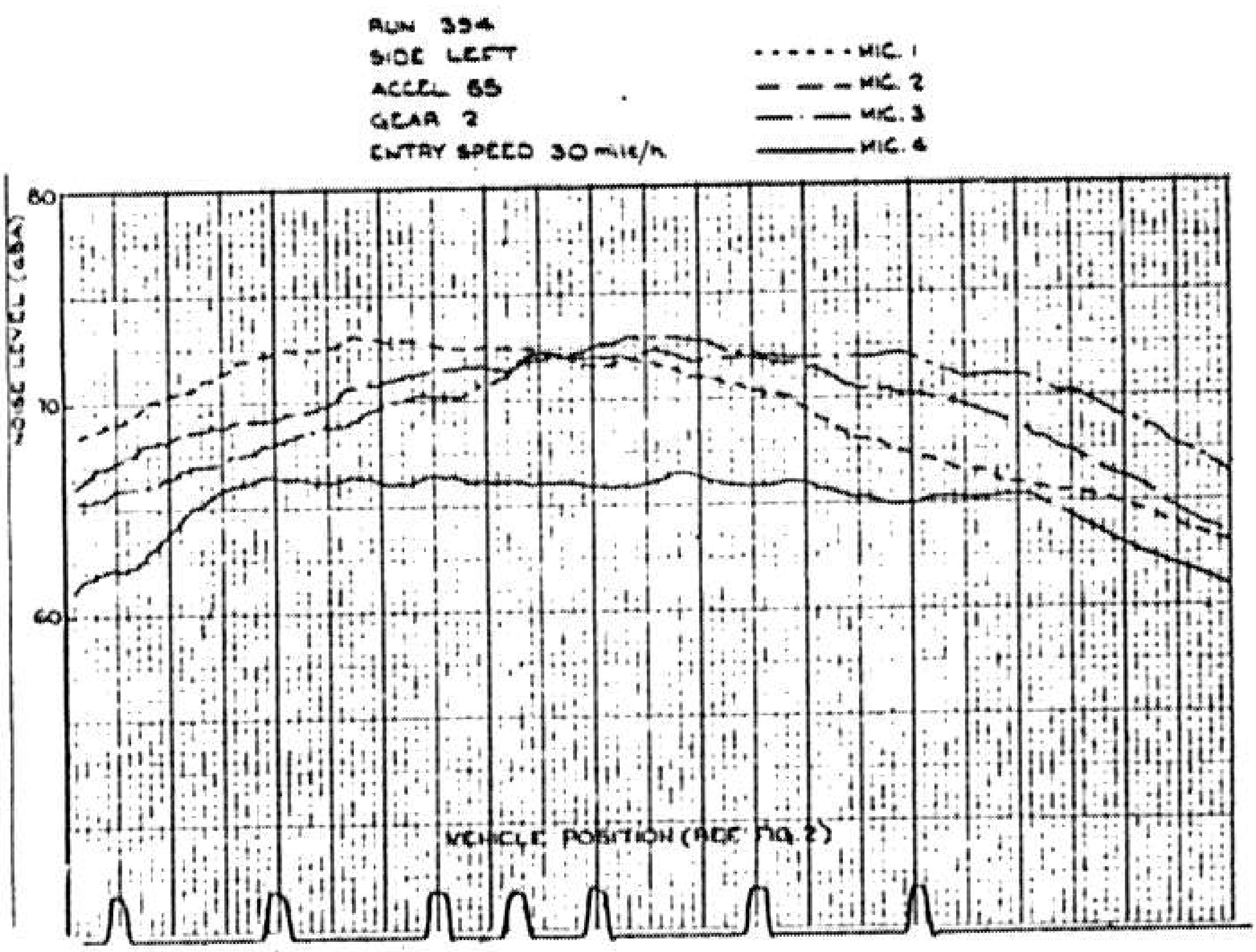


FIGURE 3-21. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - FIESTA

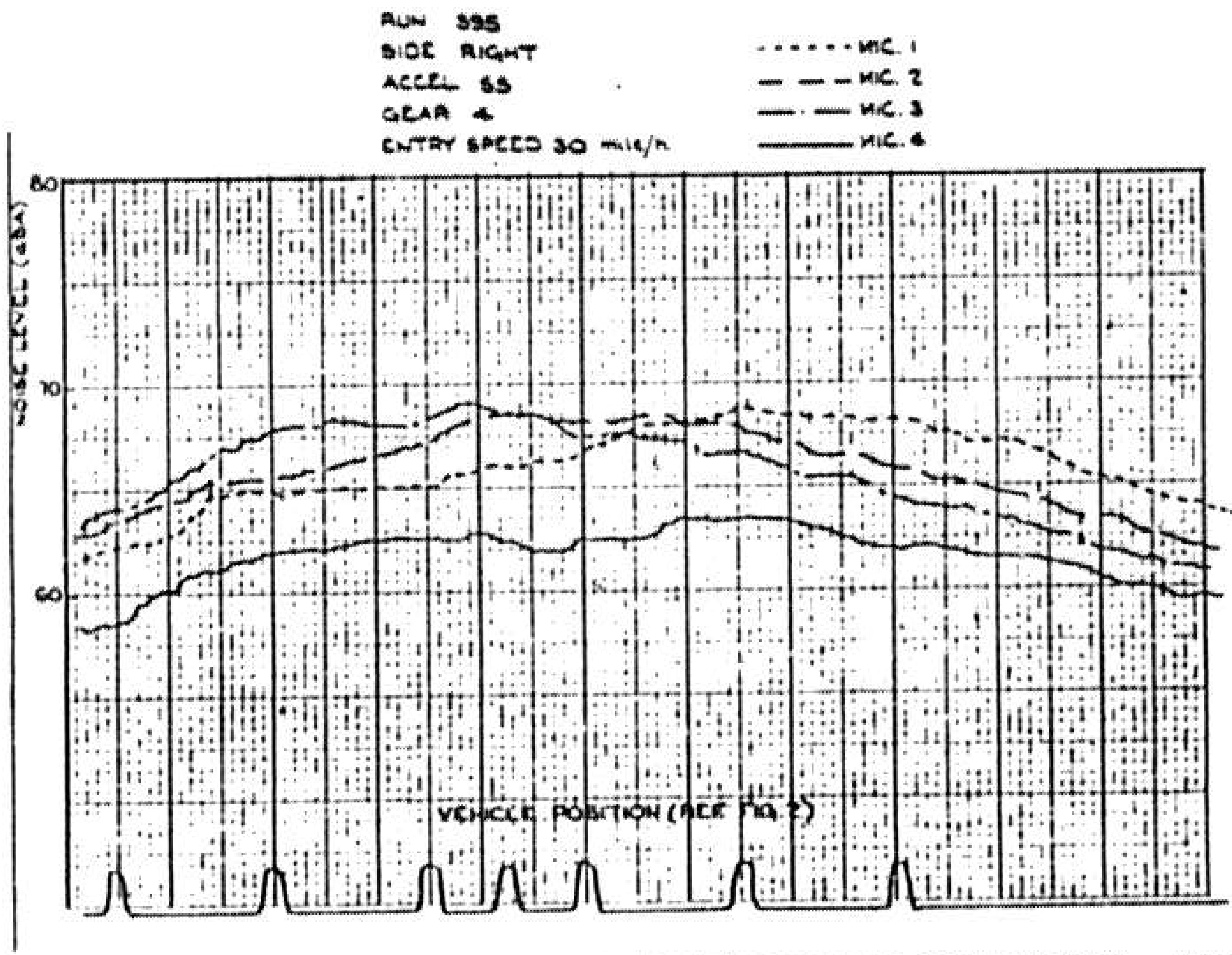


FIGURE 3-22. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - FIESTA

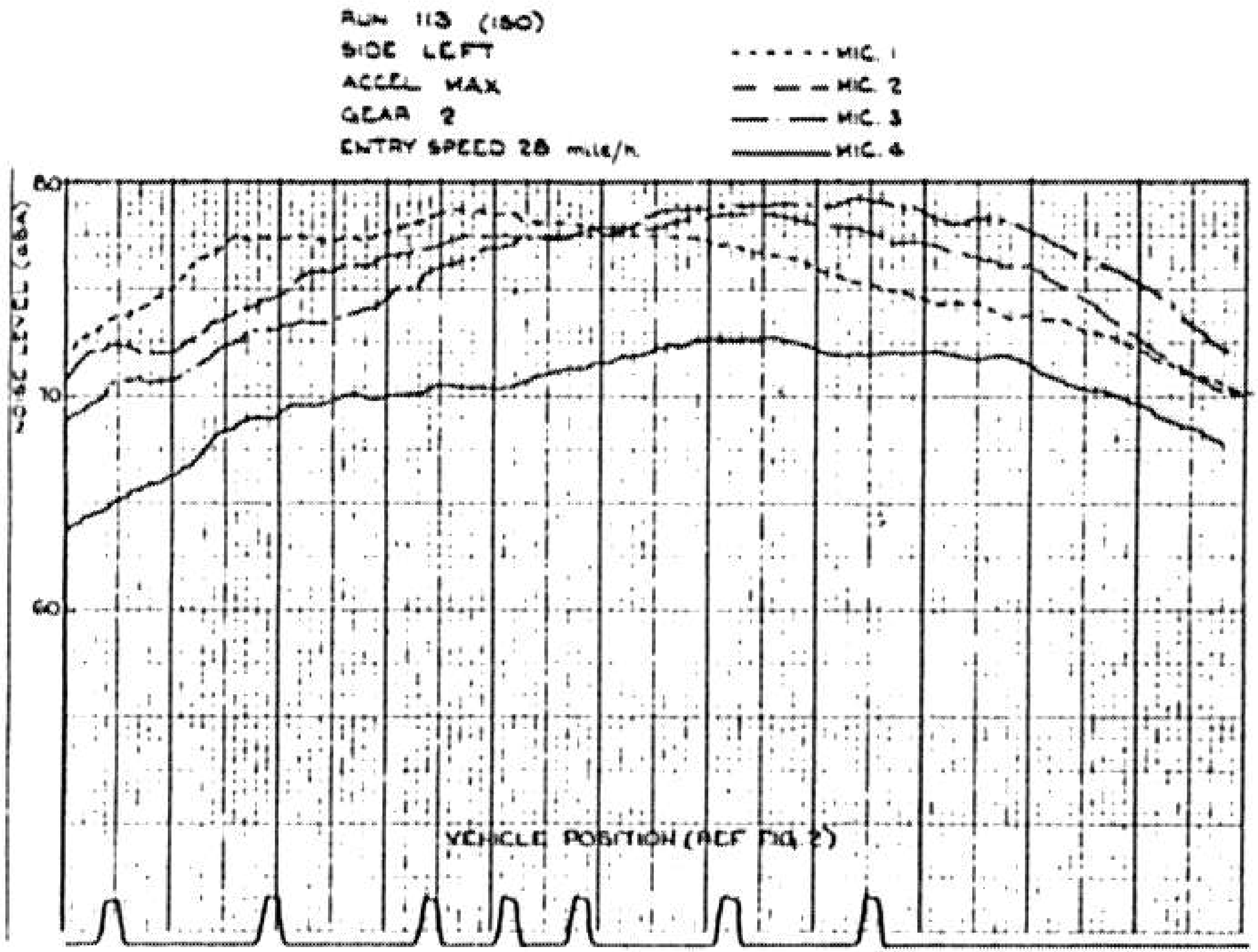


FIGURE 3-23. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - OPEL 2100D(T/C)

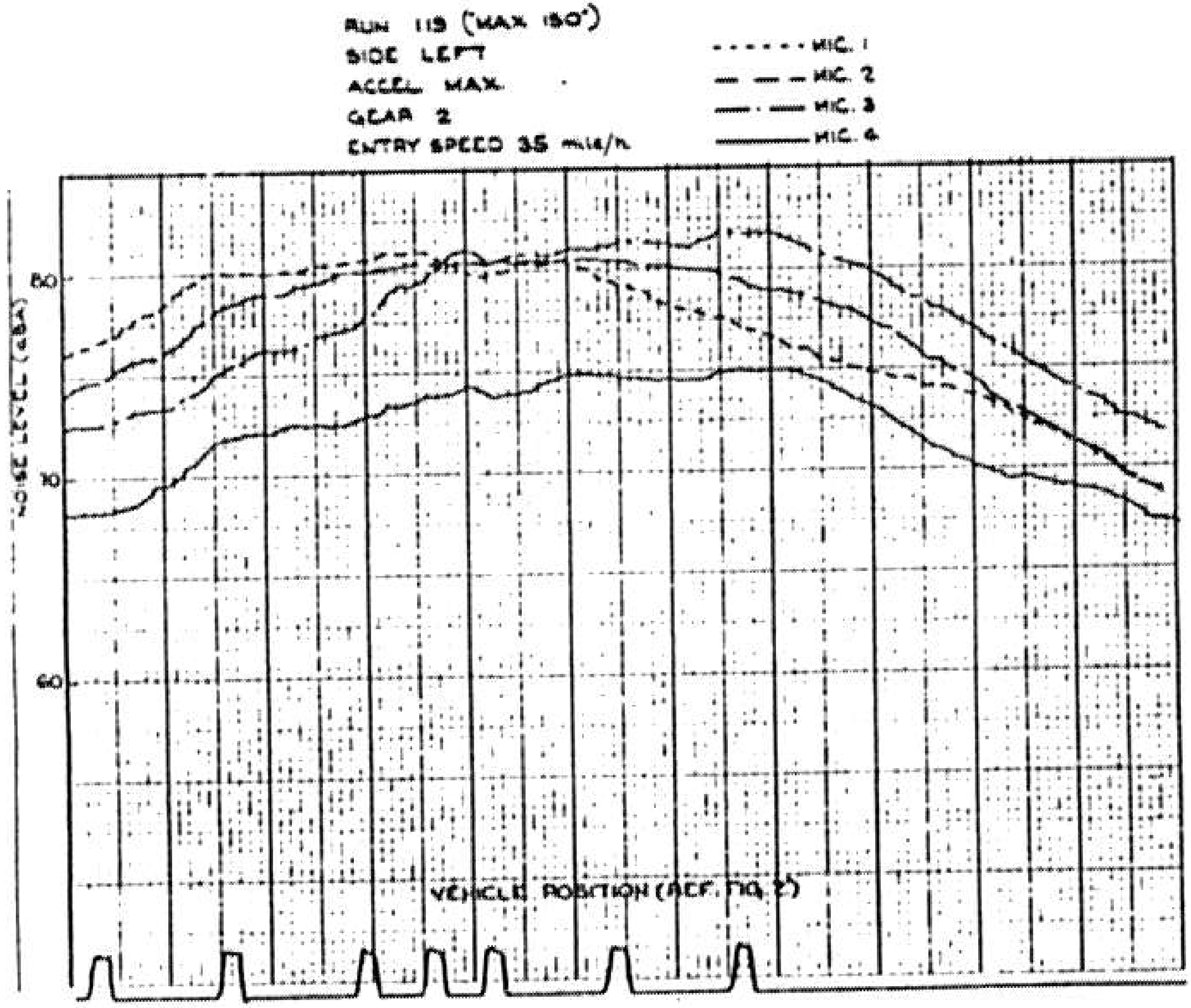


FIGURE 3-24. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - OPEL 2100D(T/C)

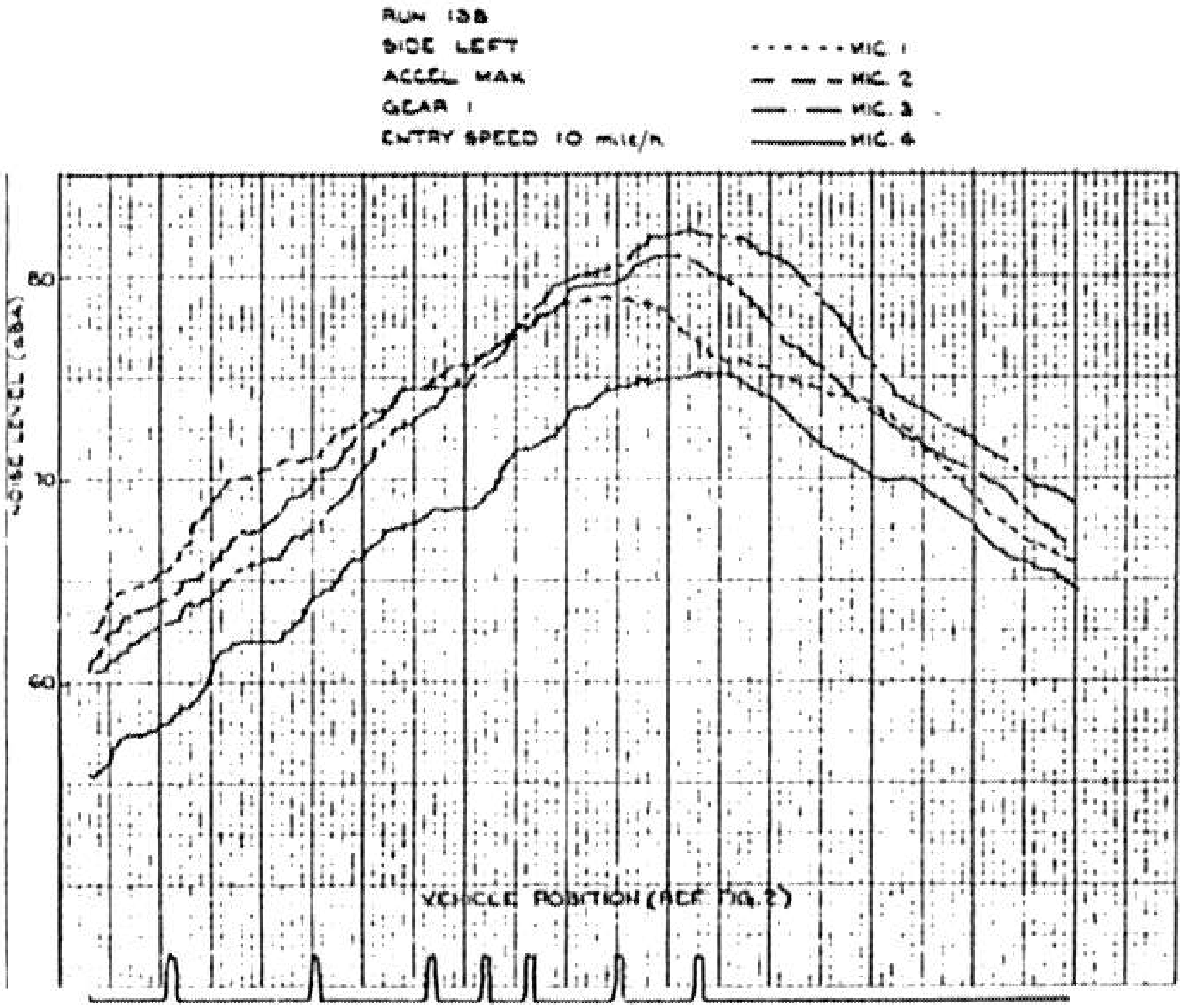


FIGURE 3-25. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - OPEL 2100D(T/C)

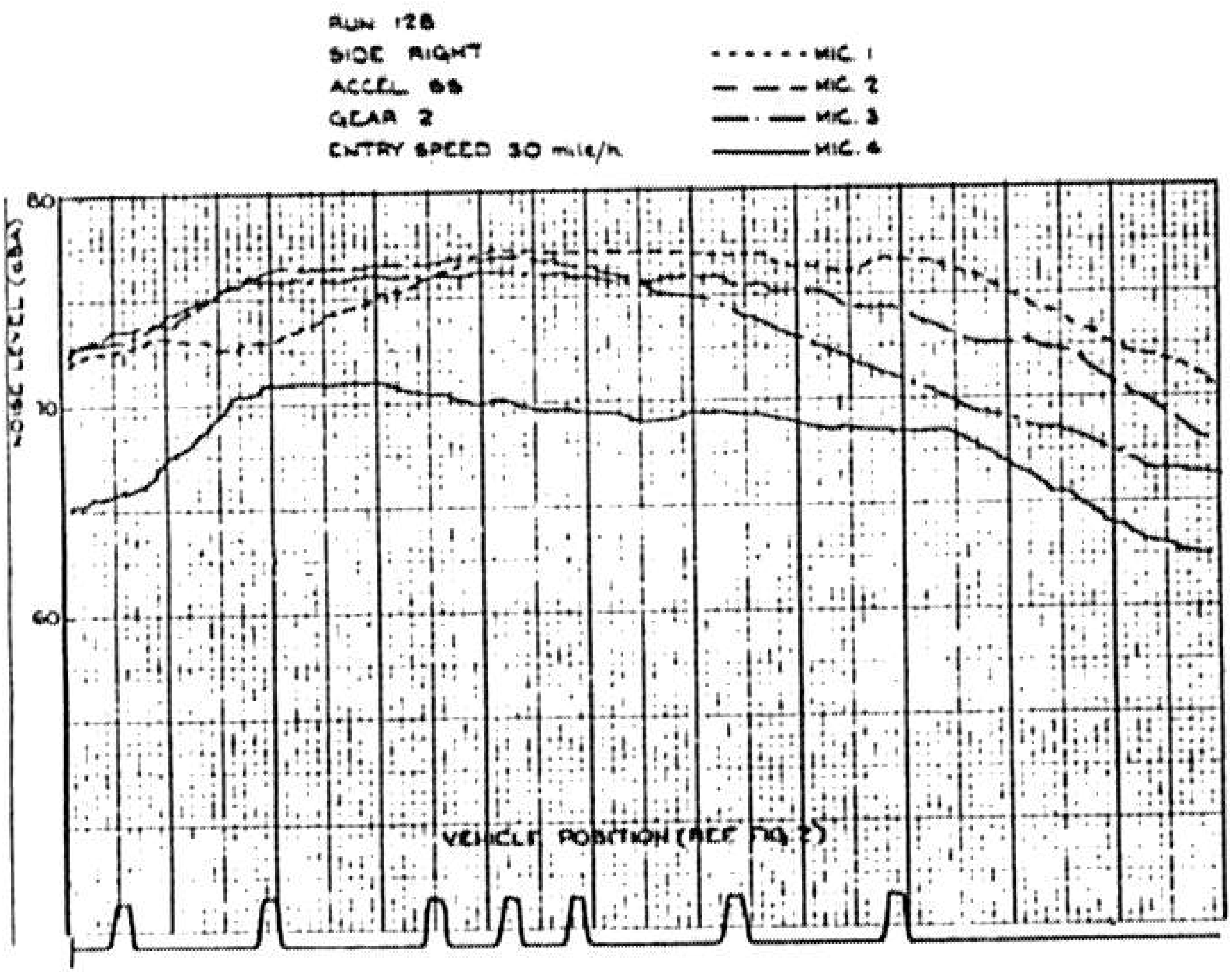


FIGURE 3-26. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - OPEL 2100D(T/C)

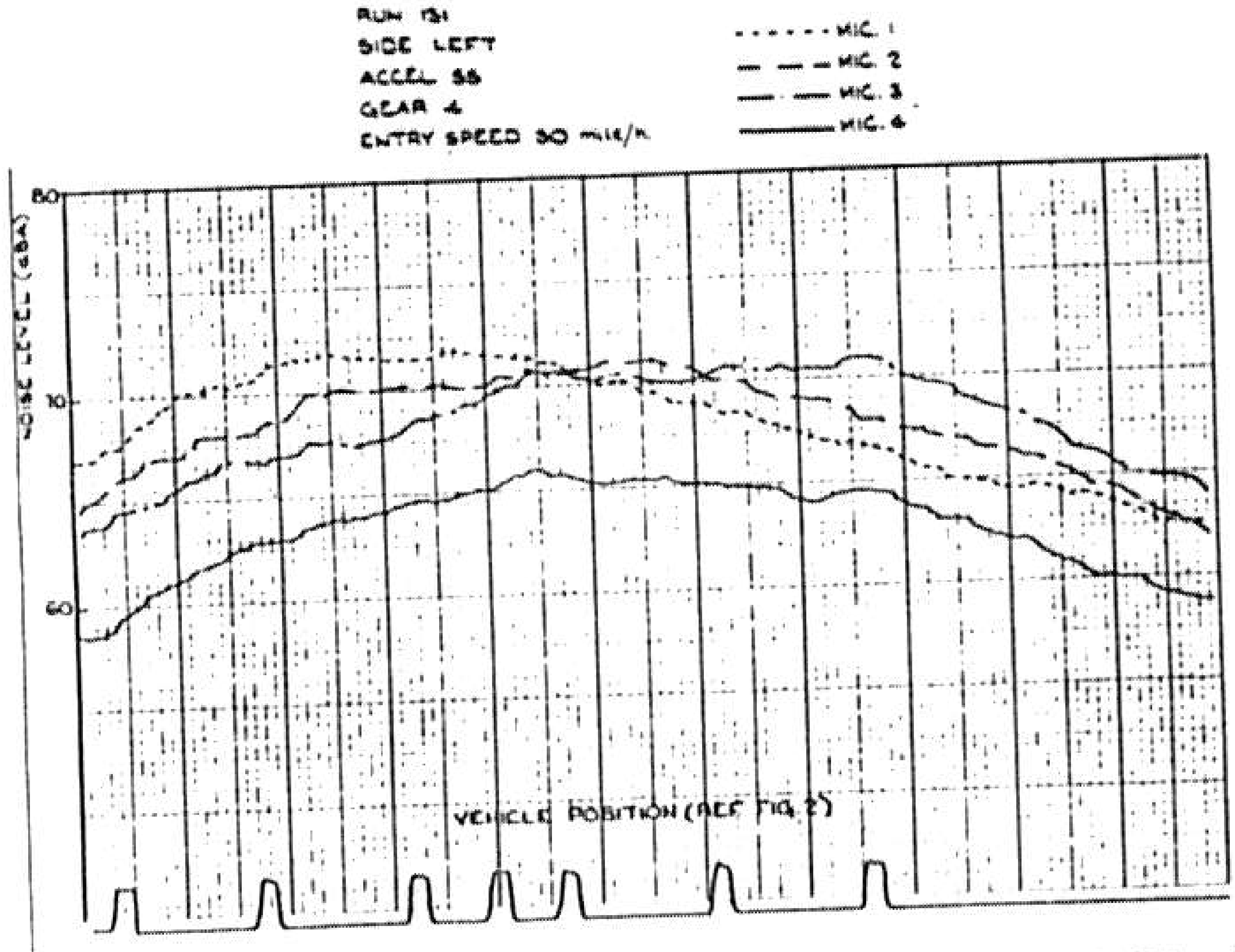


FIGURE 3-27. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - OPEL 2100D(T/C)

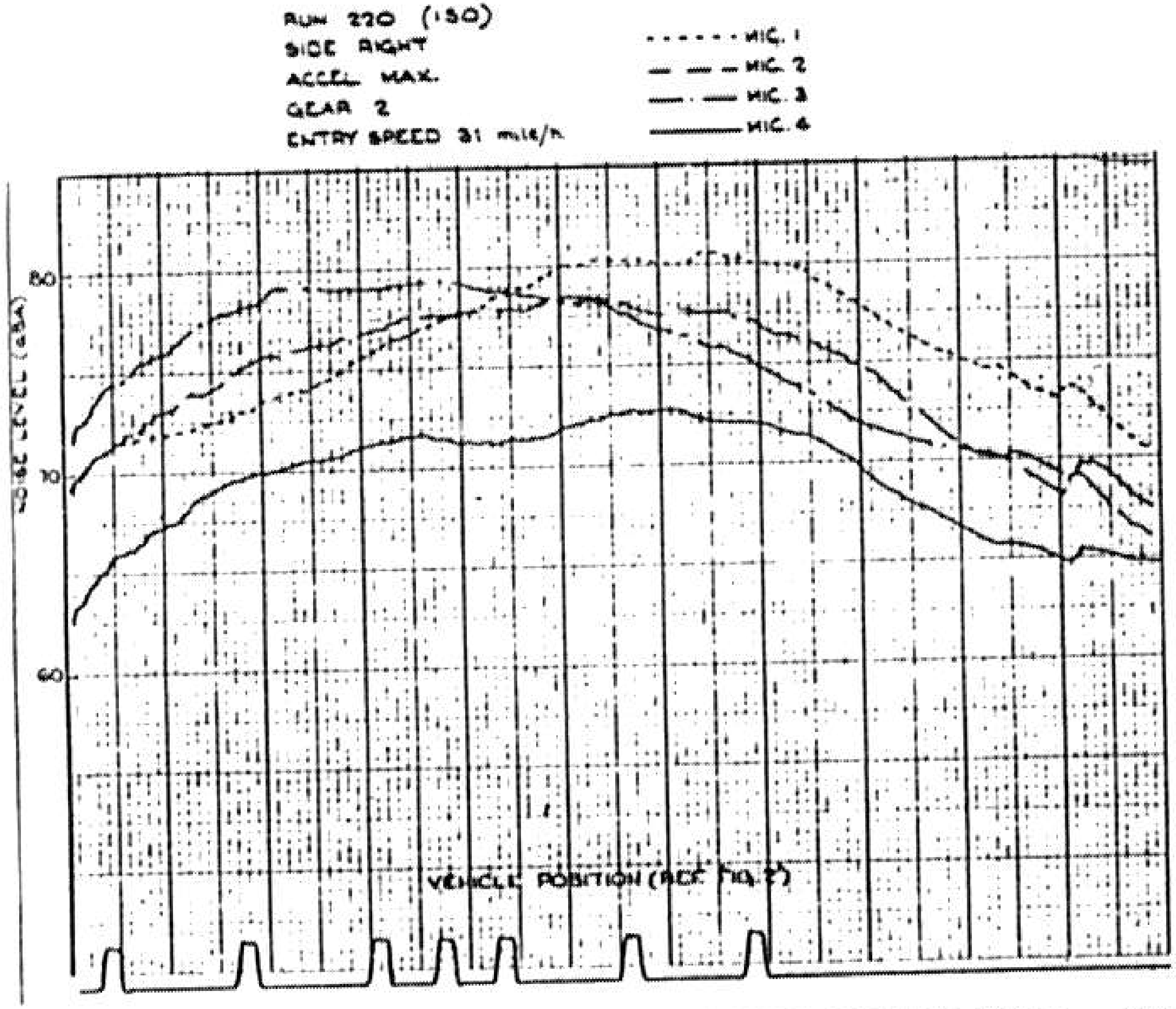


FIGURE 3-28. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - CORTINA 1600

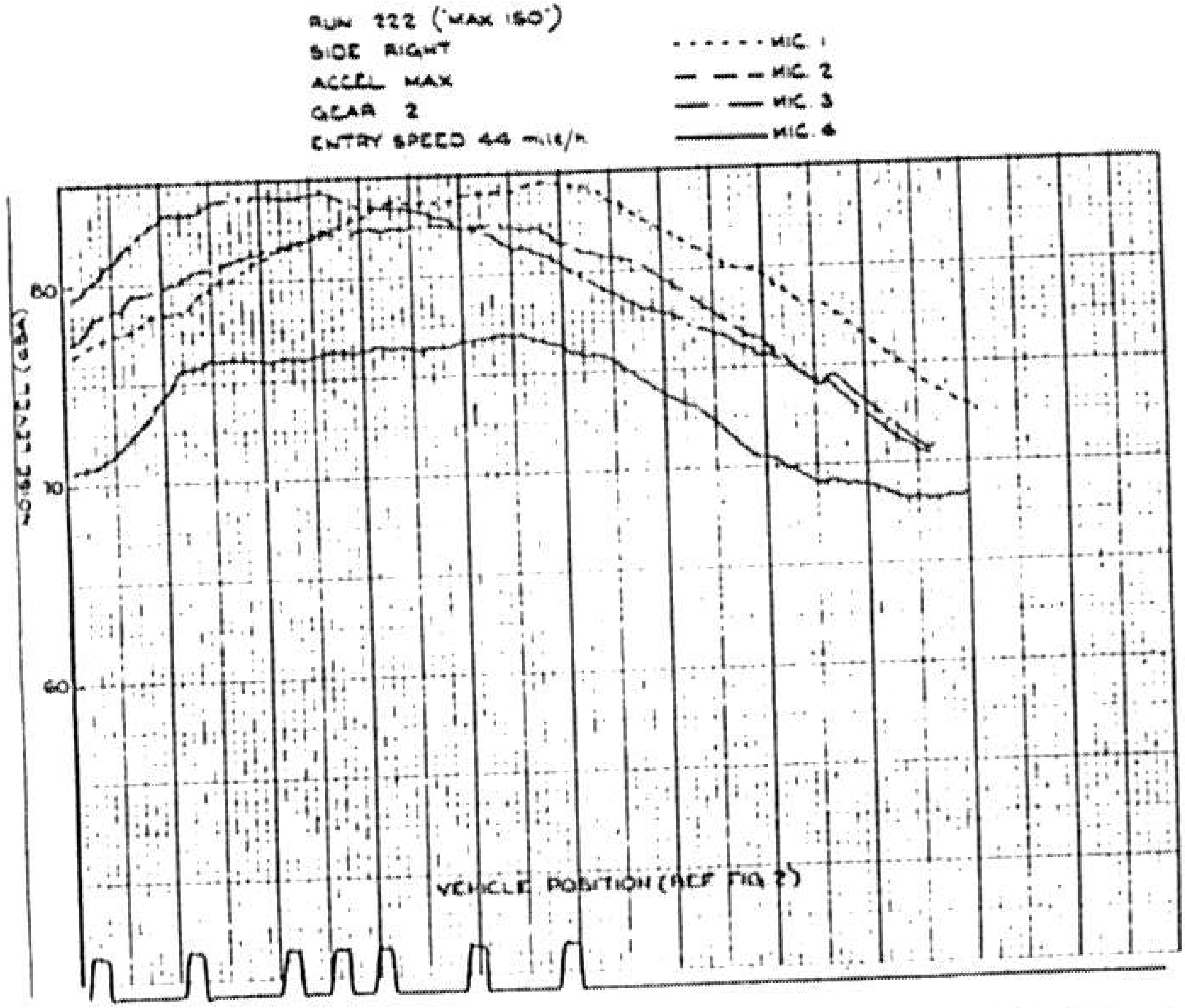


FIGURE 3-29. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - CORTINA 1600

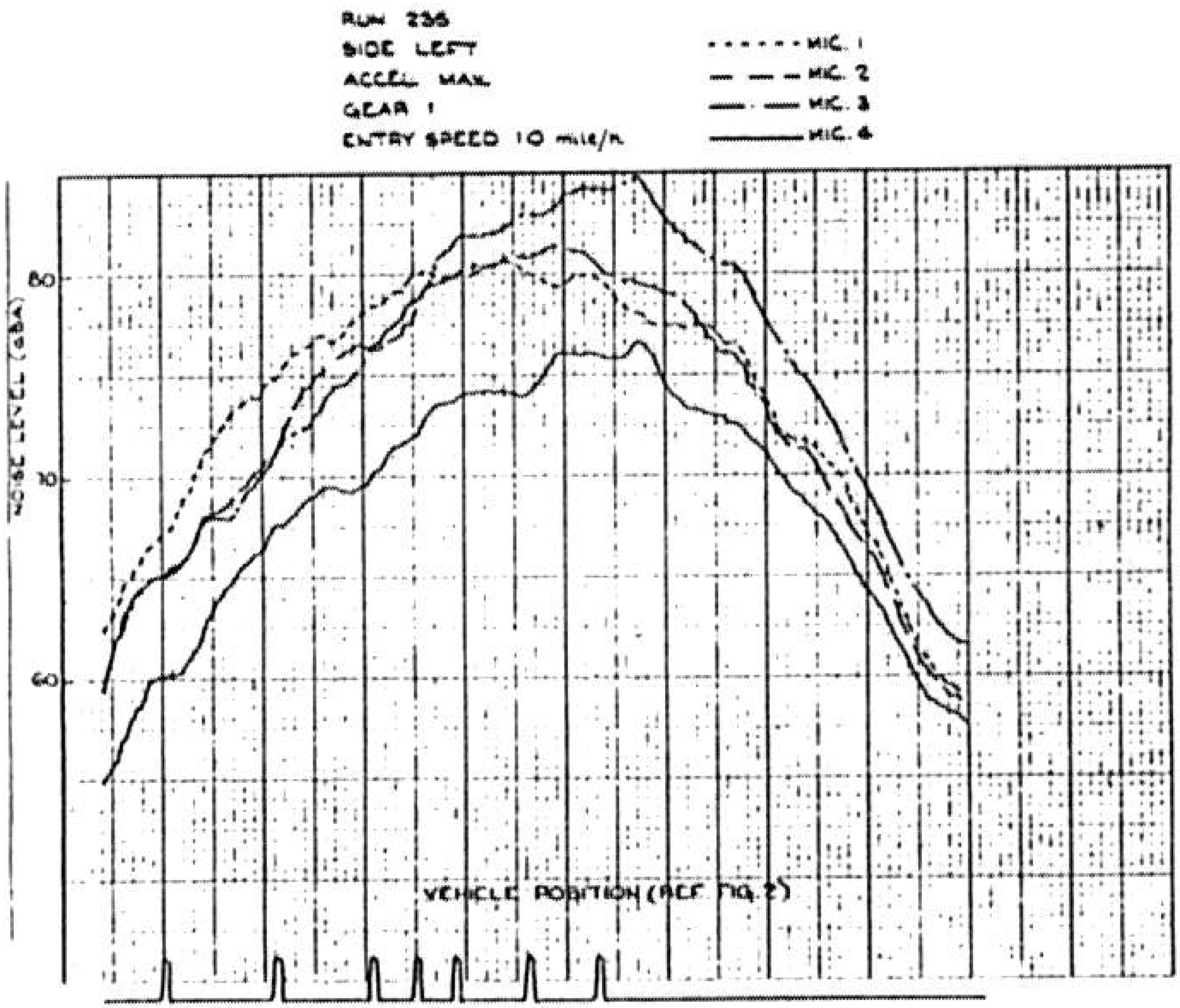


FIGURE 3-30. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - CORTINA 1600

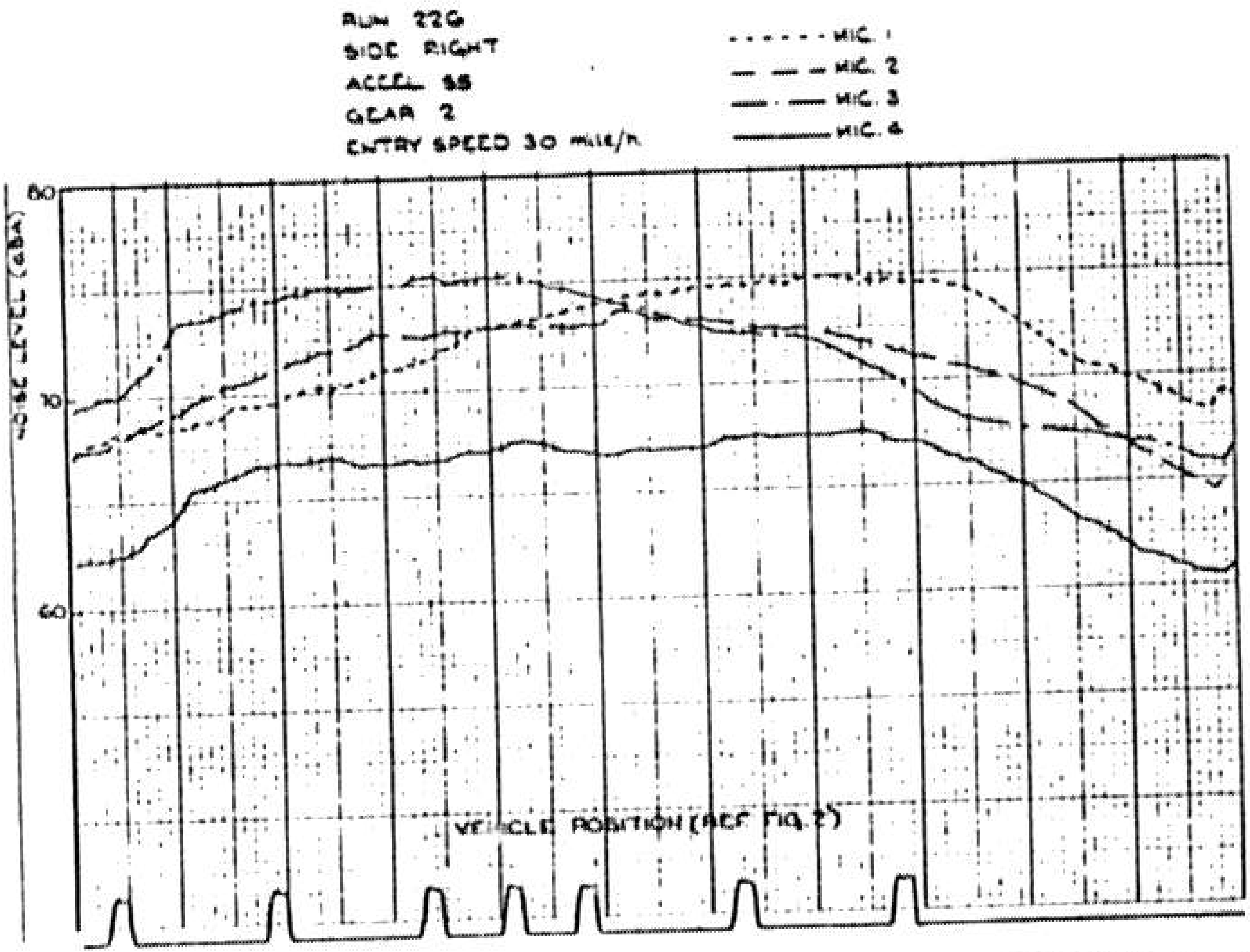


FIGURE 3-31. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - CORTINA 1600

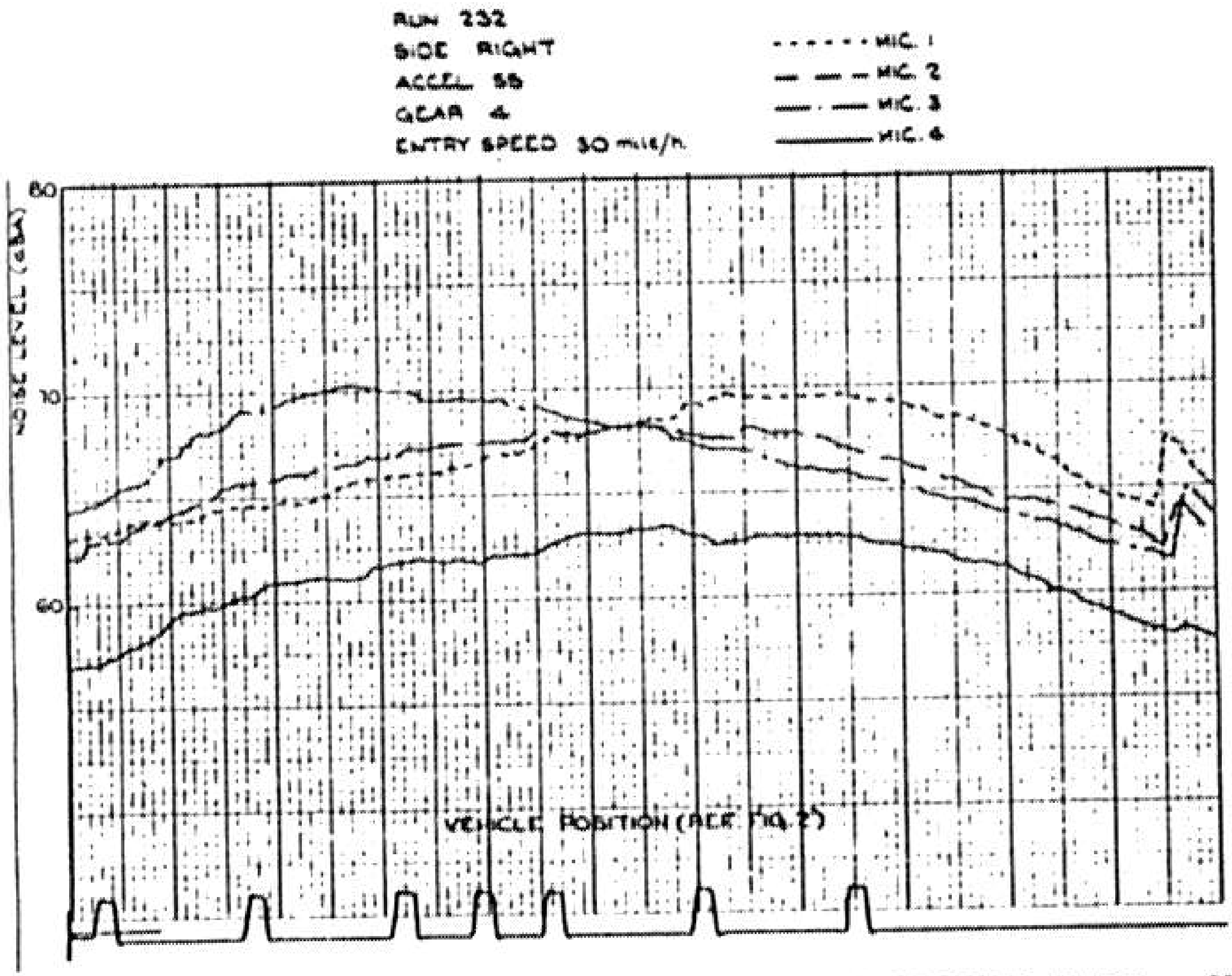


FIGURE 3-32. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - CORTINA 1600

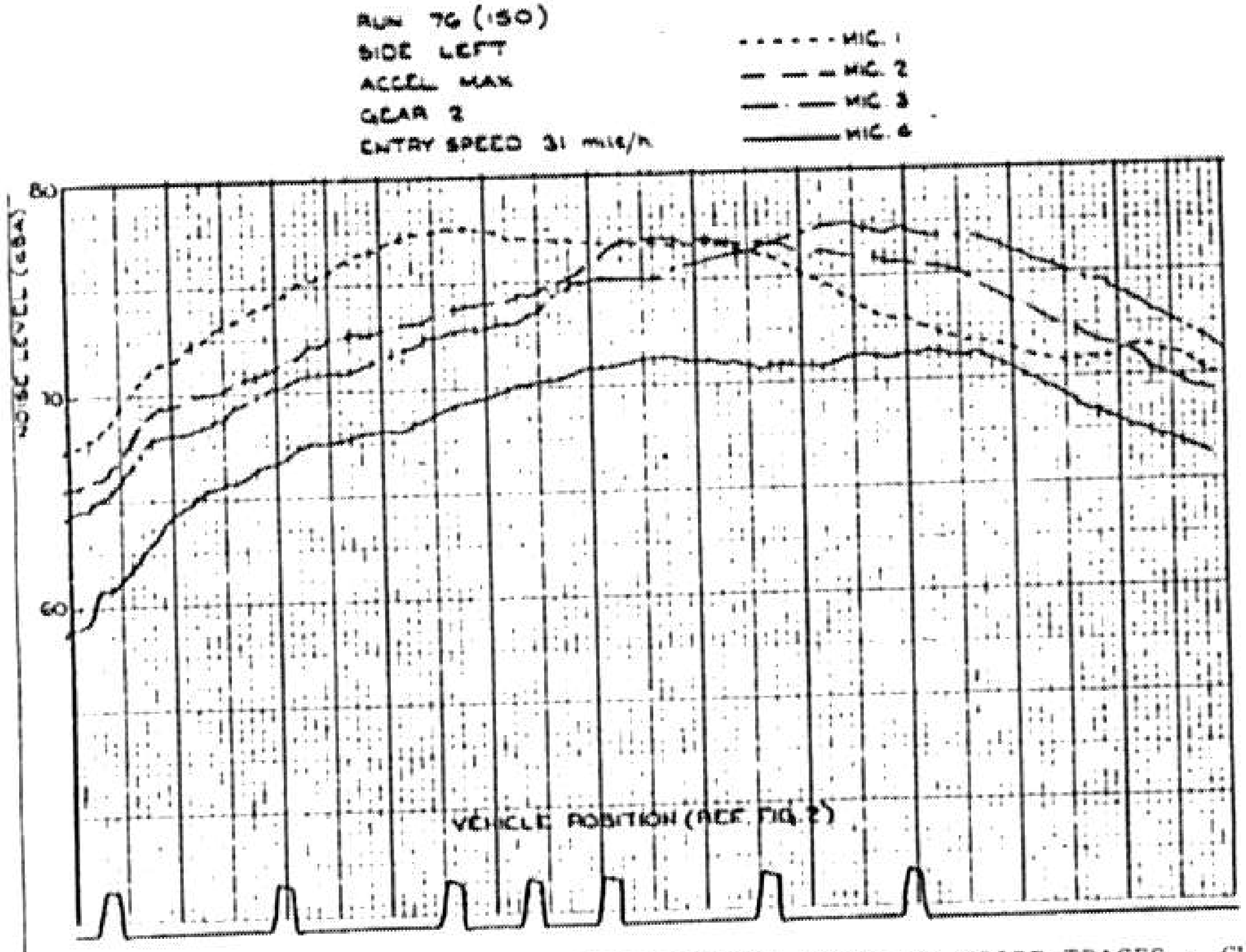


FIGURE 3-33. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - CHEVETTE GL

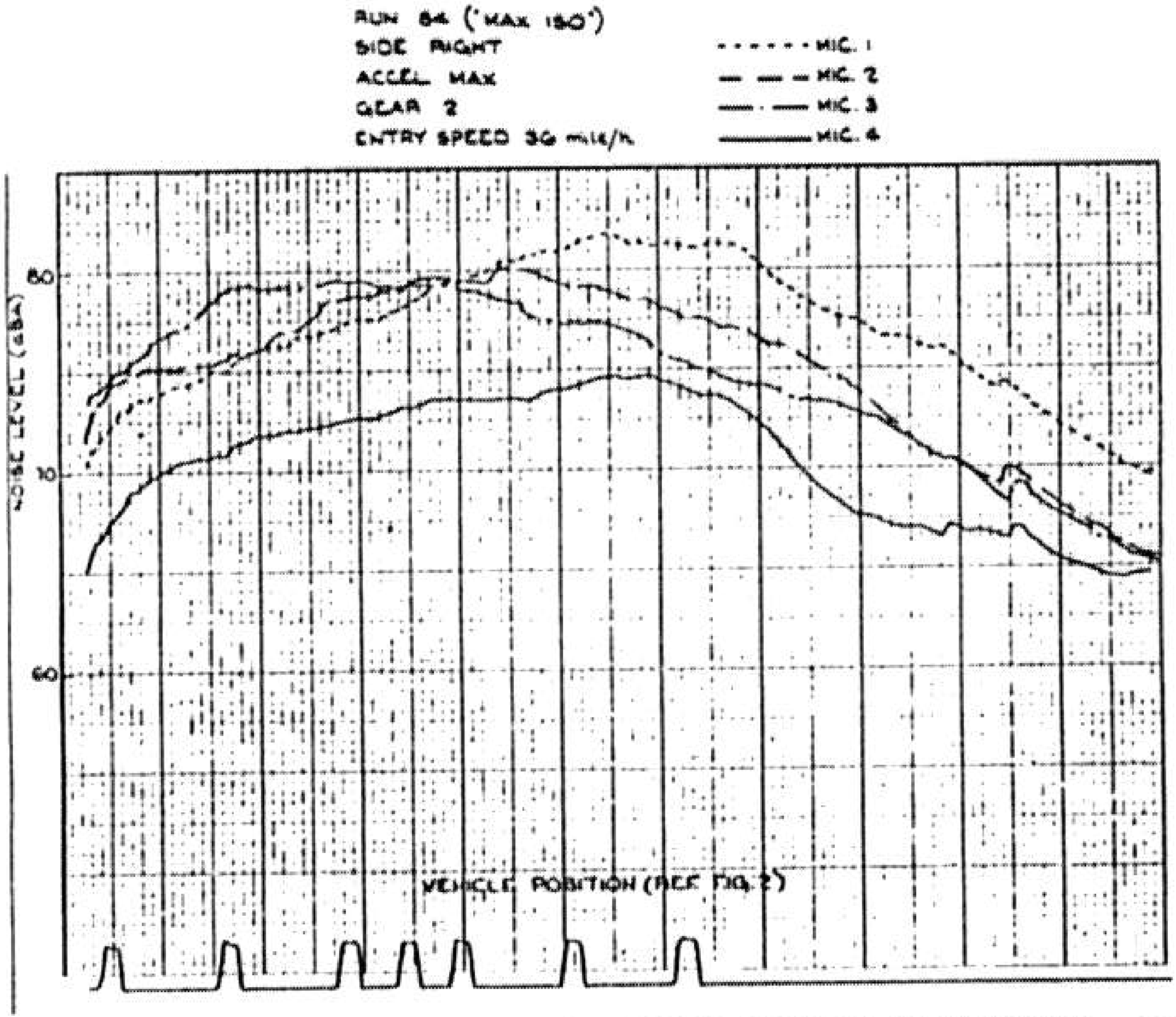


FIGURE 3-34. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - CHEVETTE GL

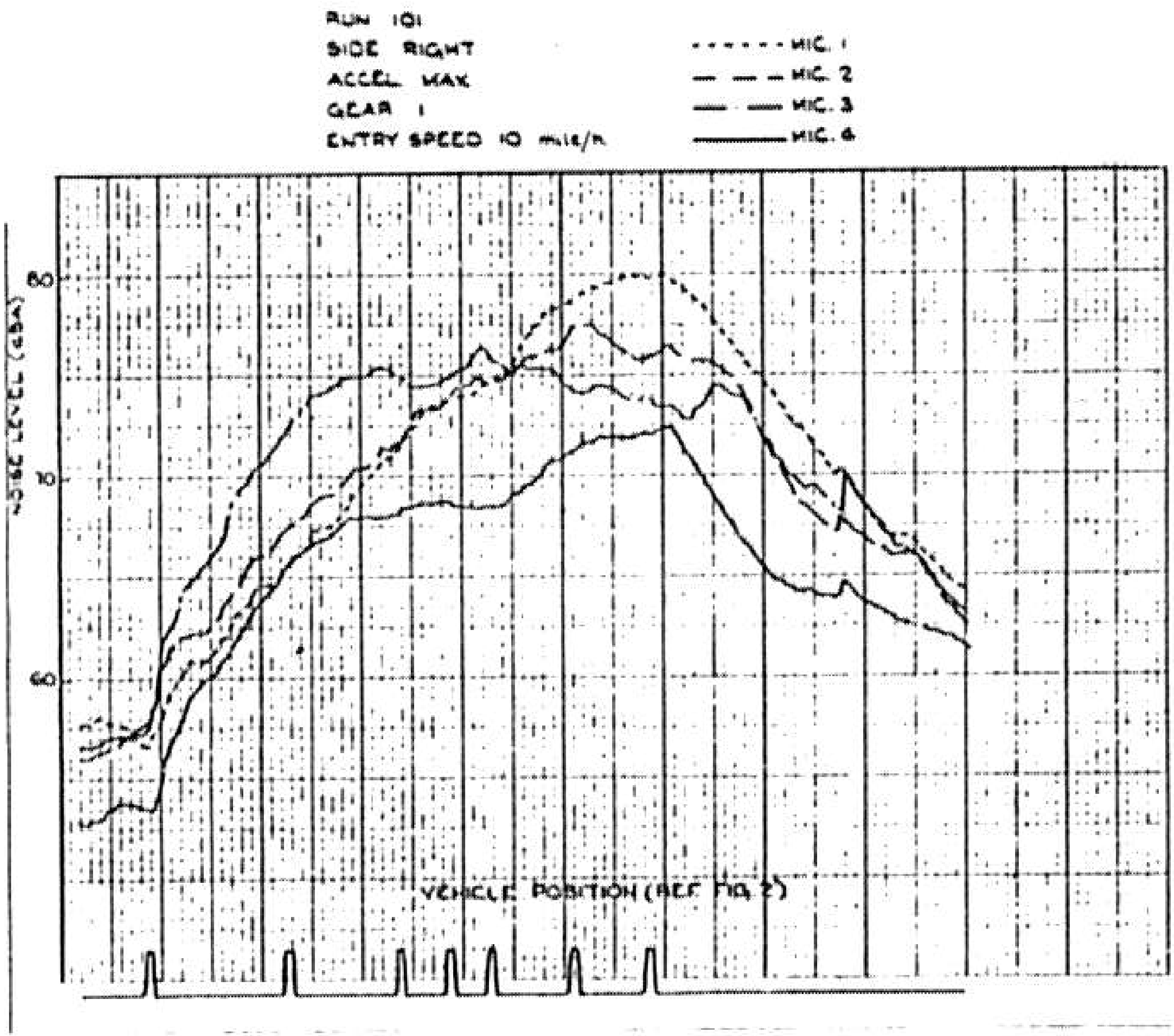


FIGURE 3-35. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - CHEVETTE GL

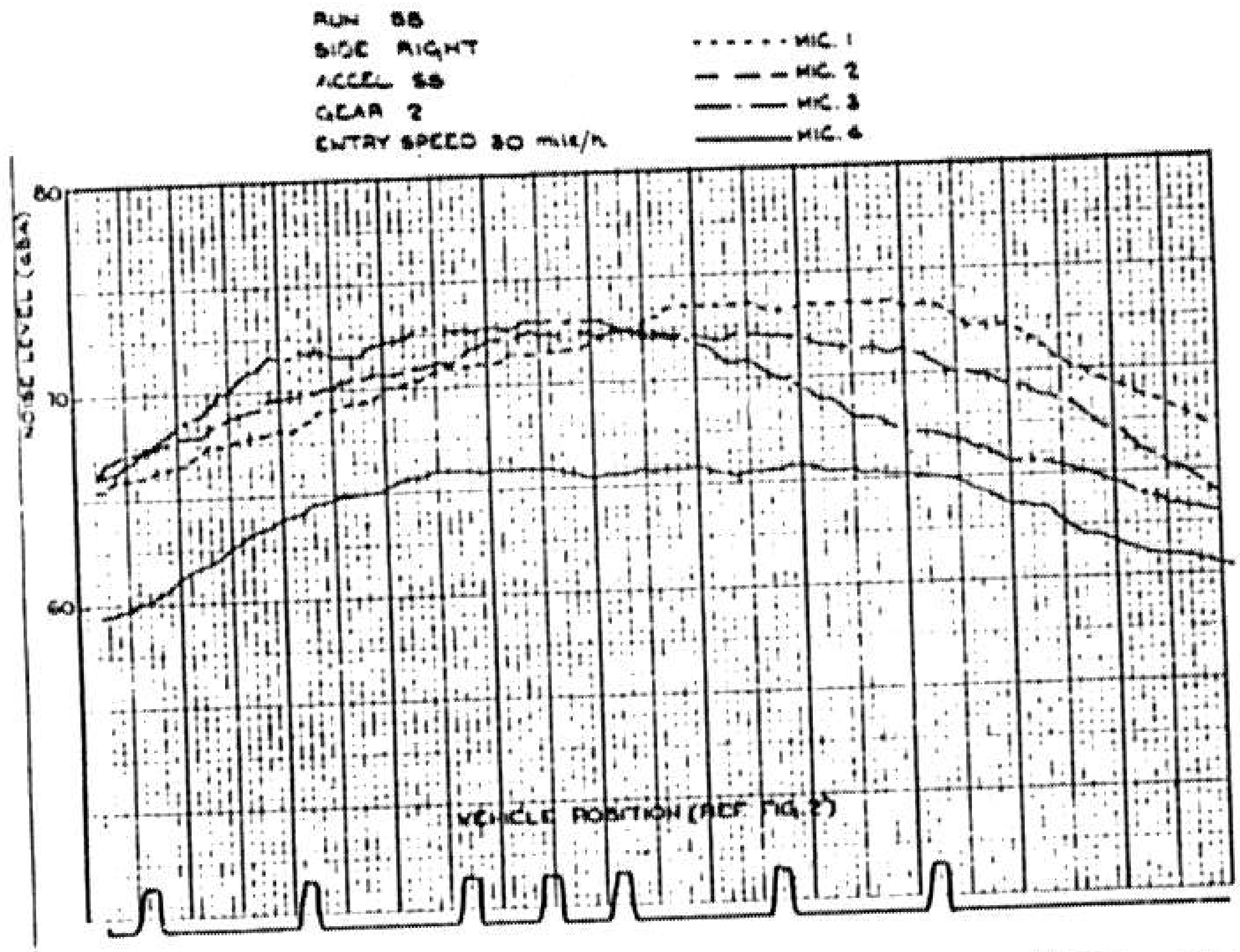


FIGURE 3-36. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - CHEVETTE GL

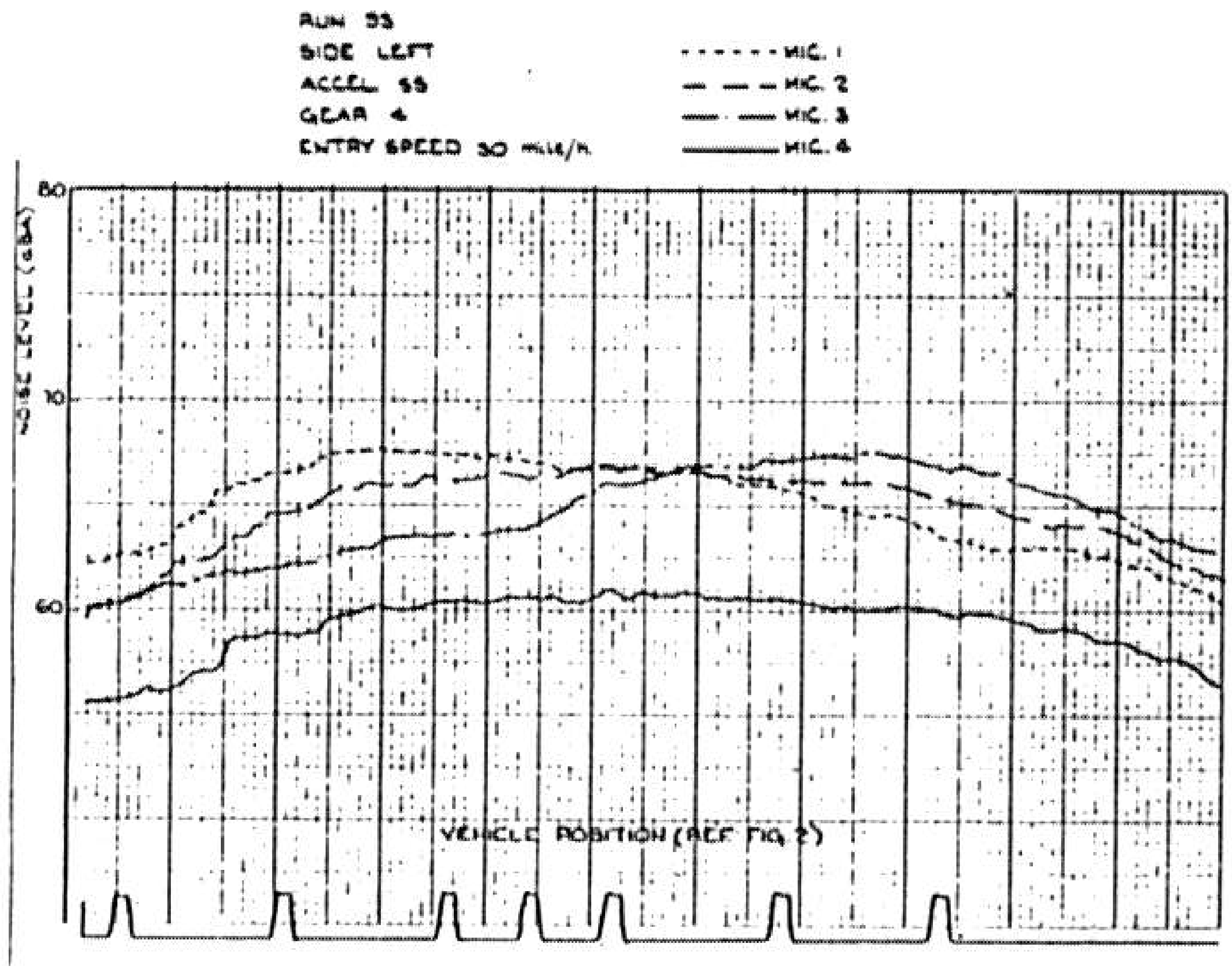


FIGURE 3-37. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - CHEVETTE GL

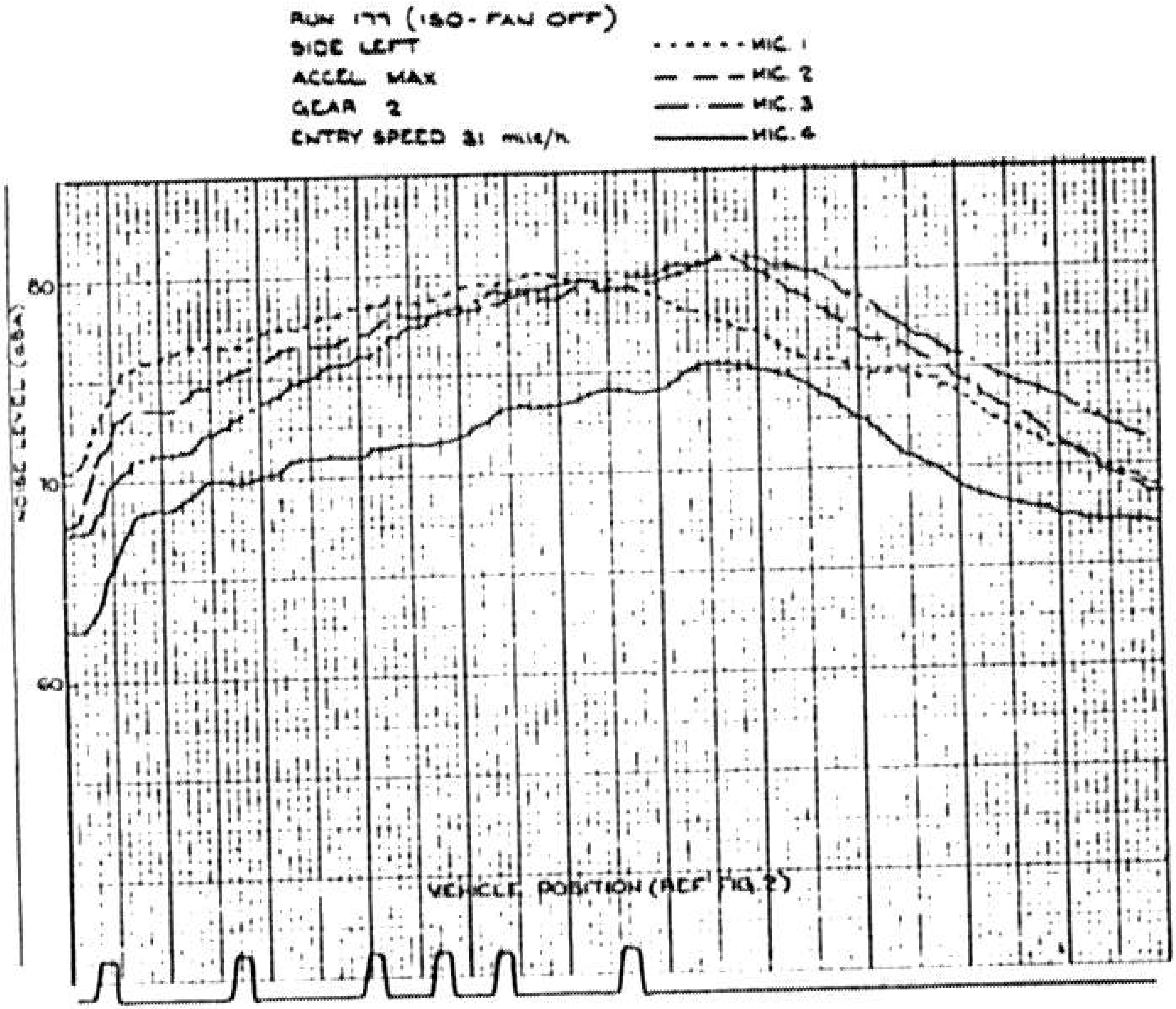


FIGURE 3-38. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - ALPINE S

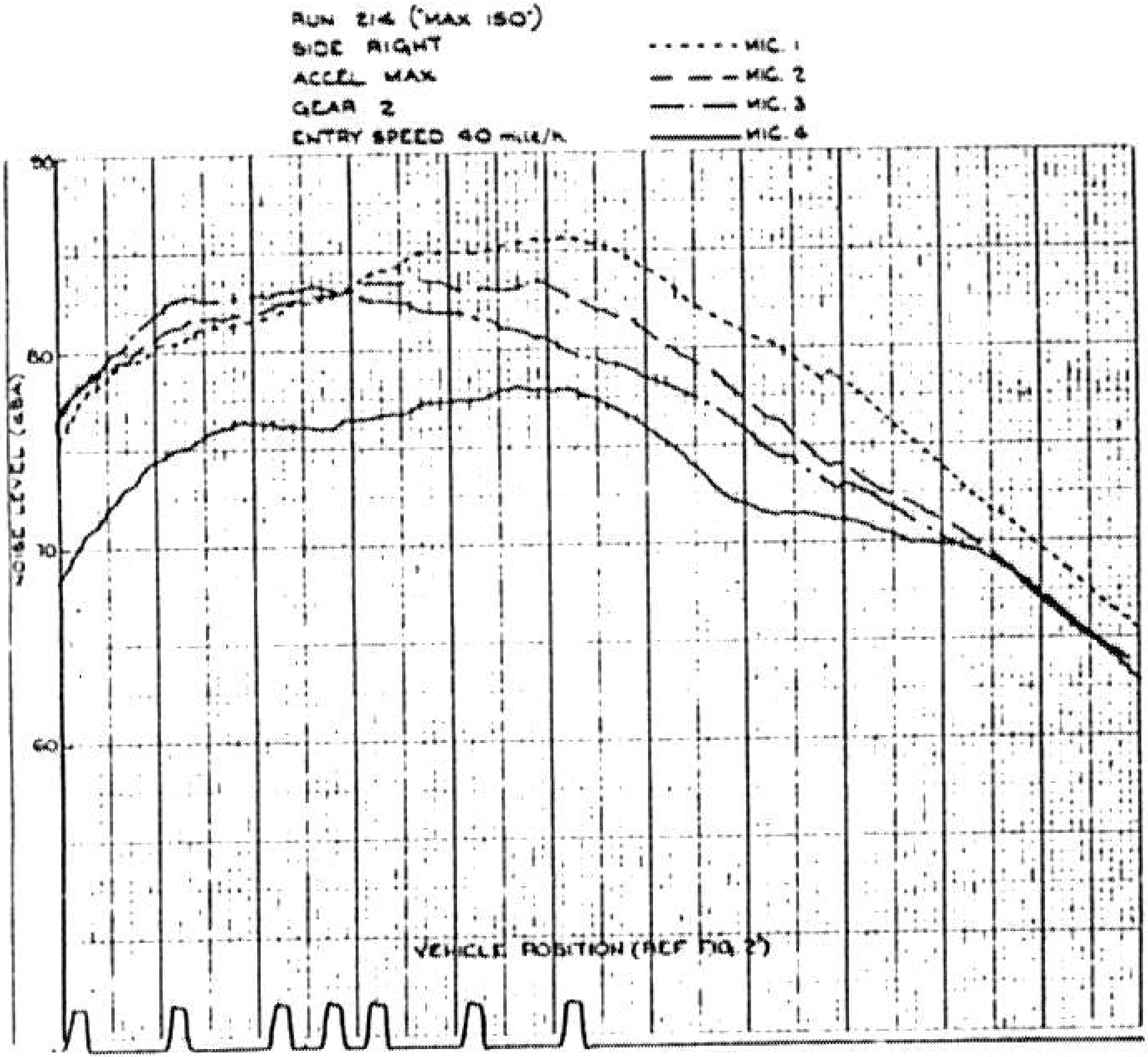


FIGURE 3-39. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - ALPINE S

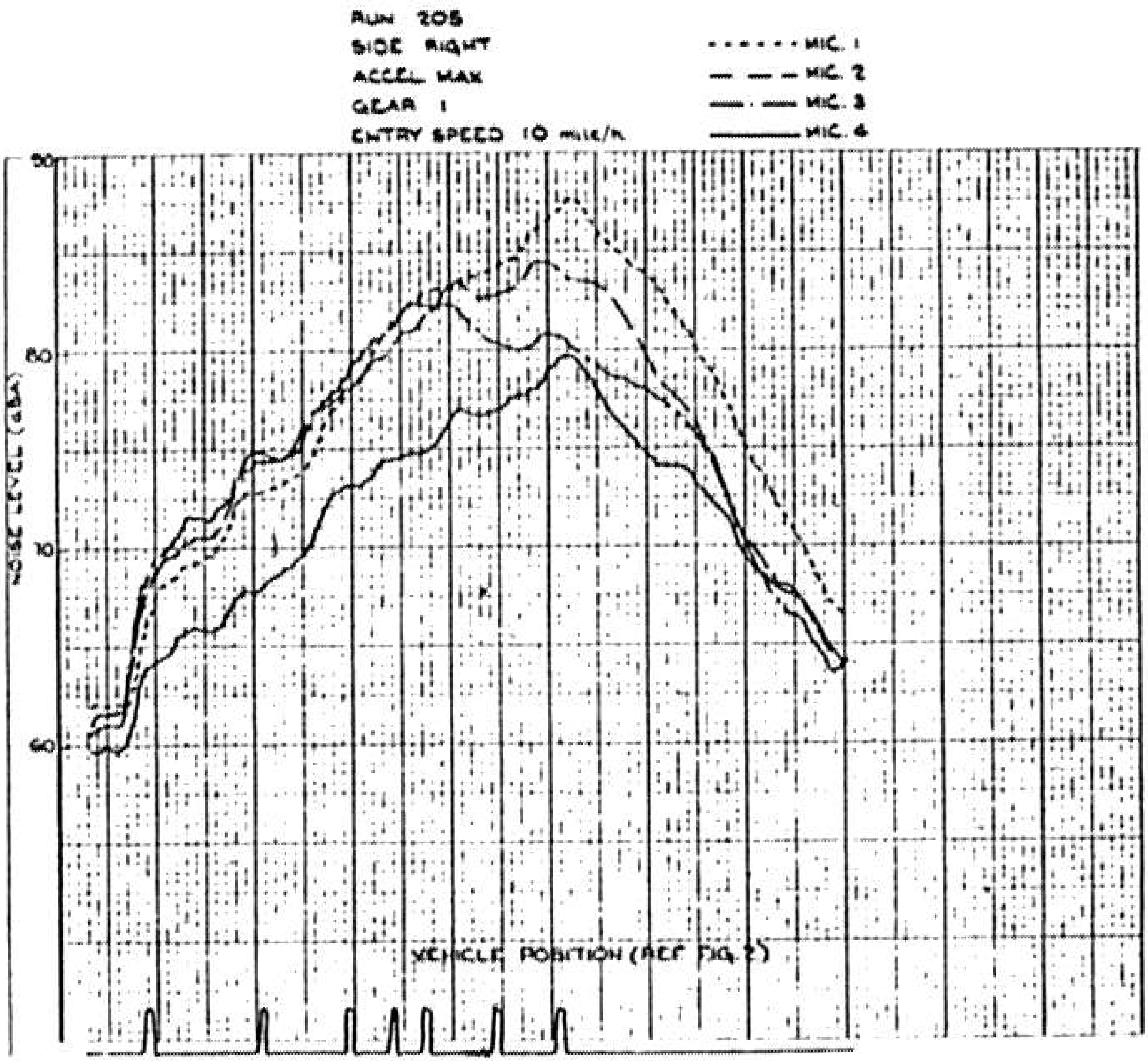


FIGURE 3-40. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - ALPINE S

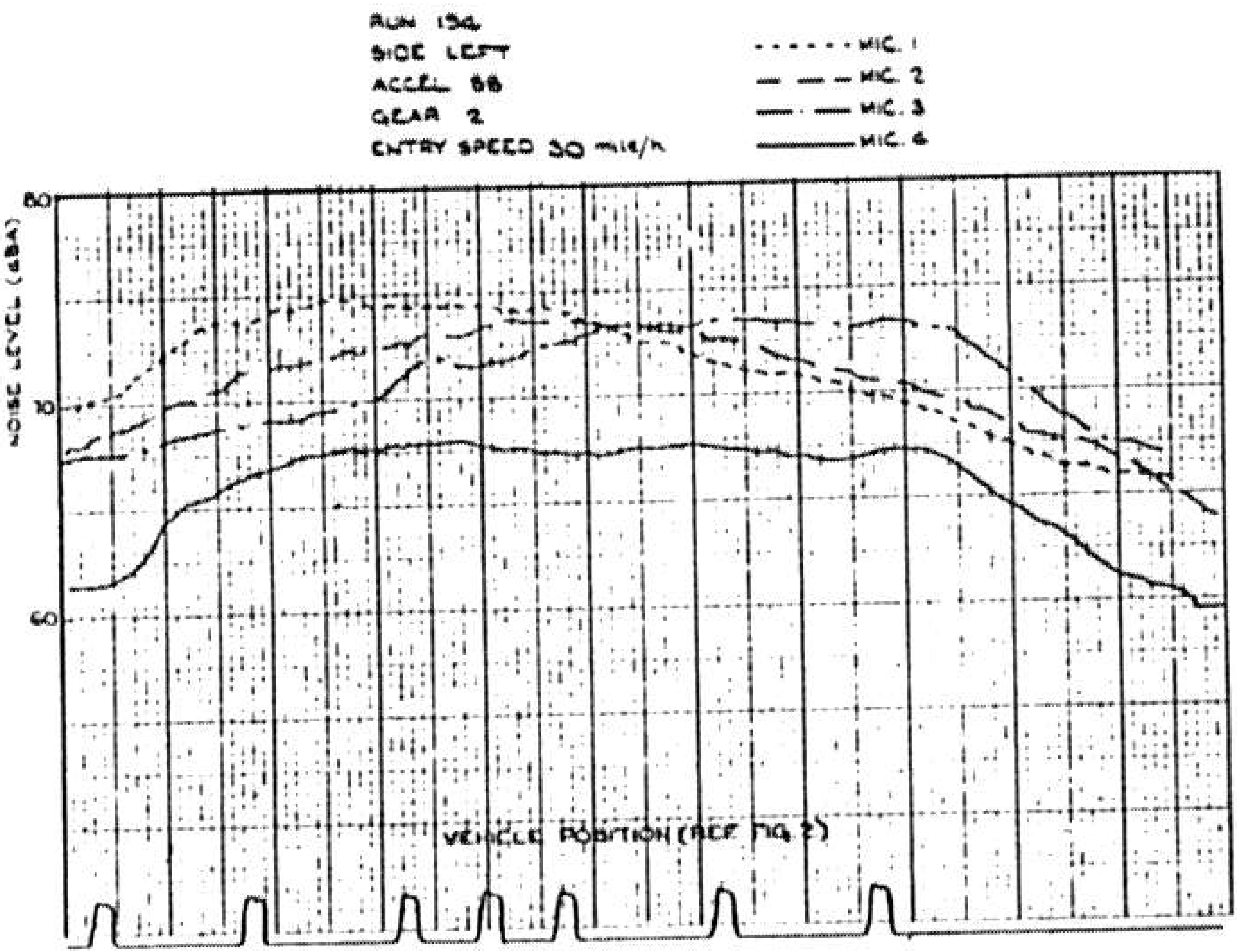


FIGURE 3-41. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - ALPINE S

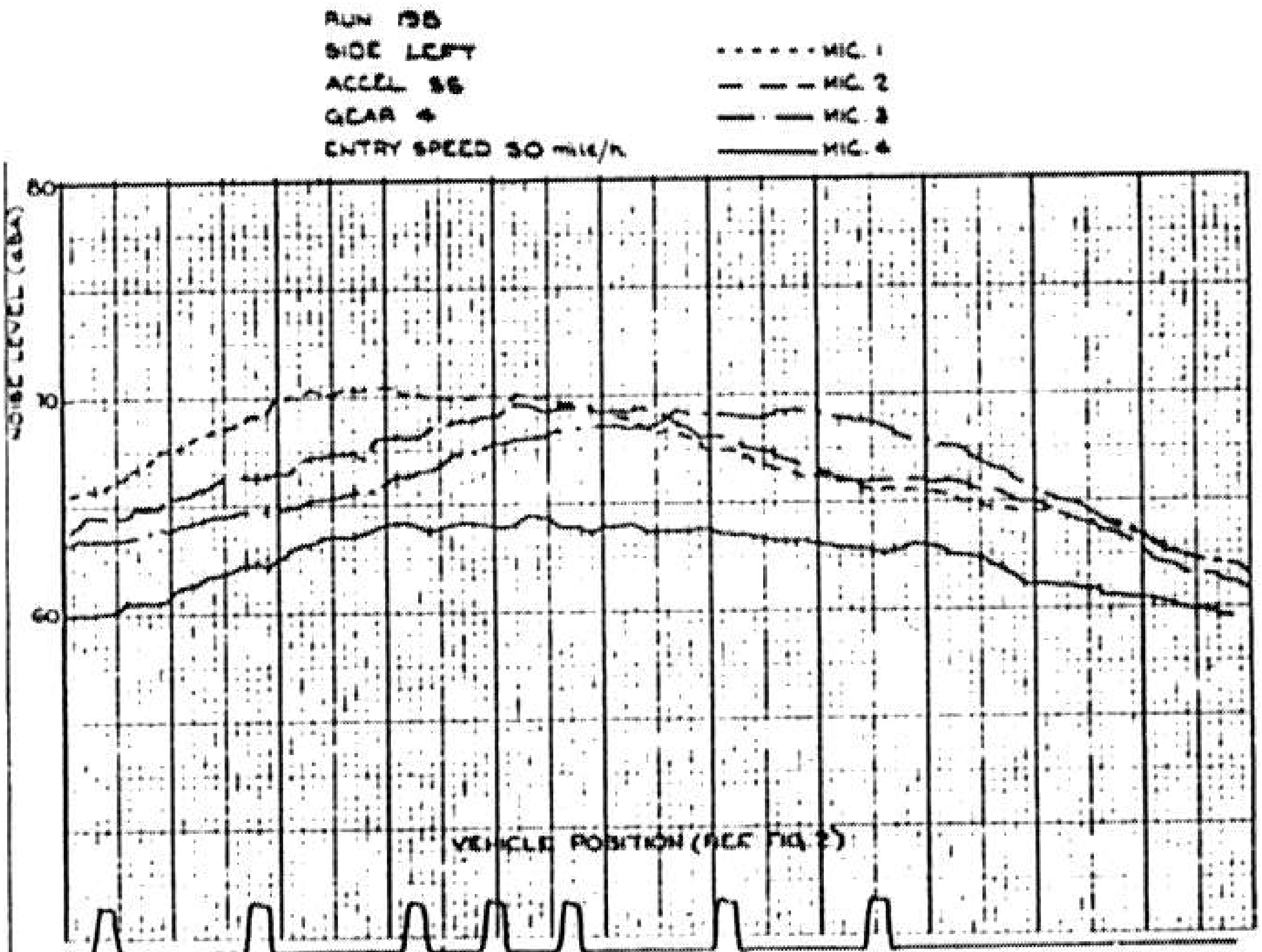


FIGURE 3-42. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - ALPINE S

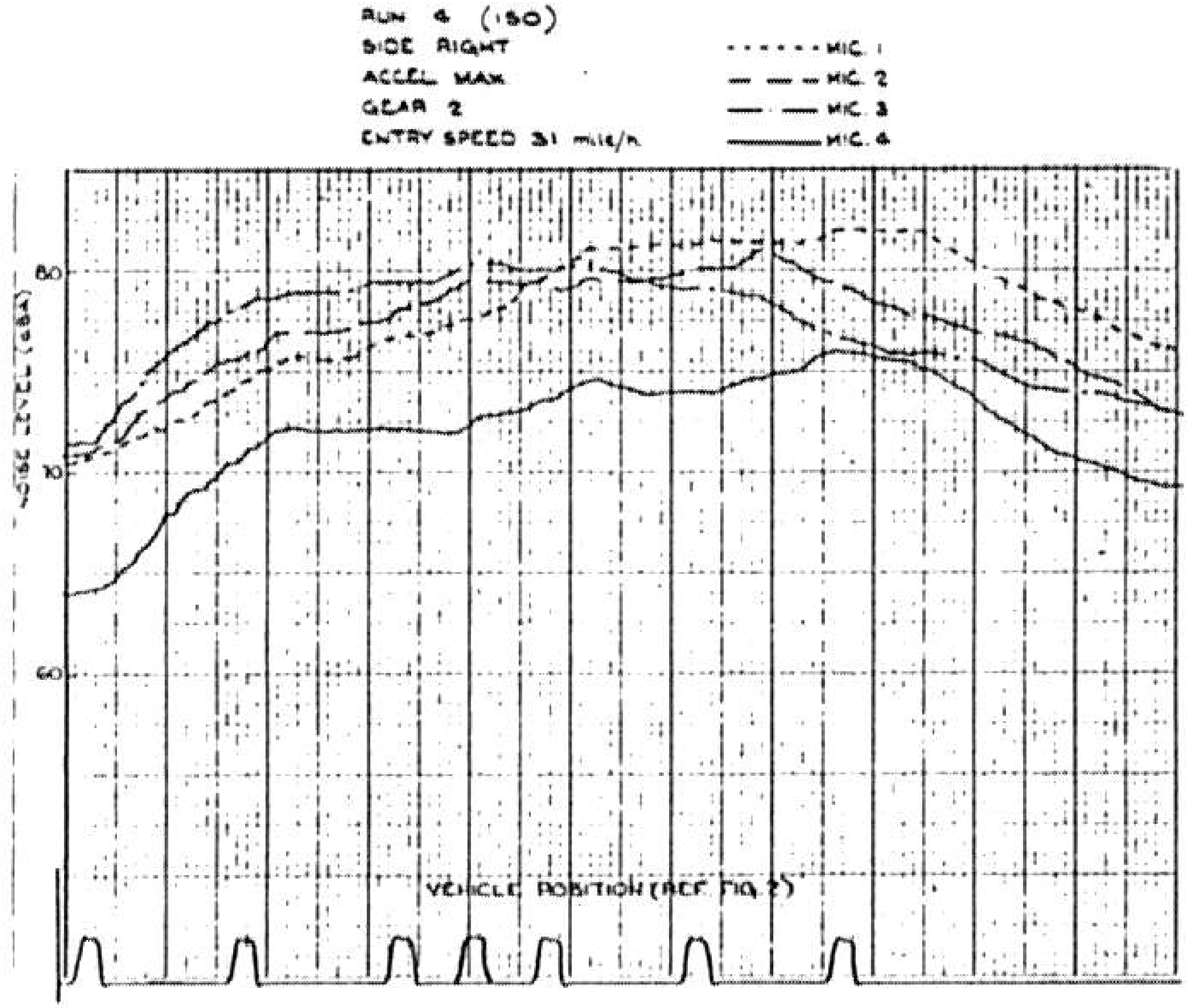


FIGURE 3-43. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - VOLVO 244GL

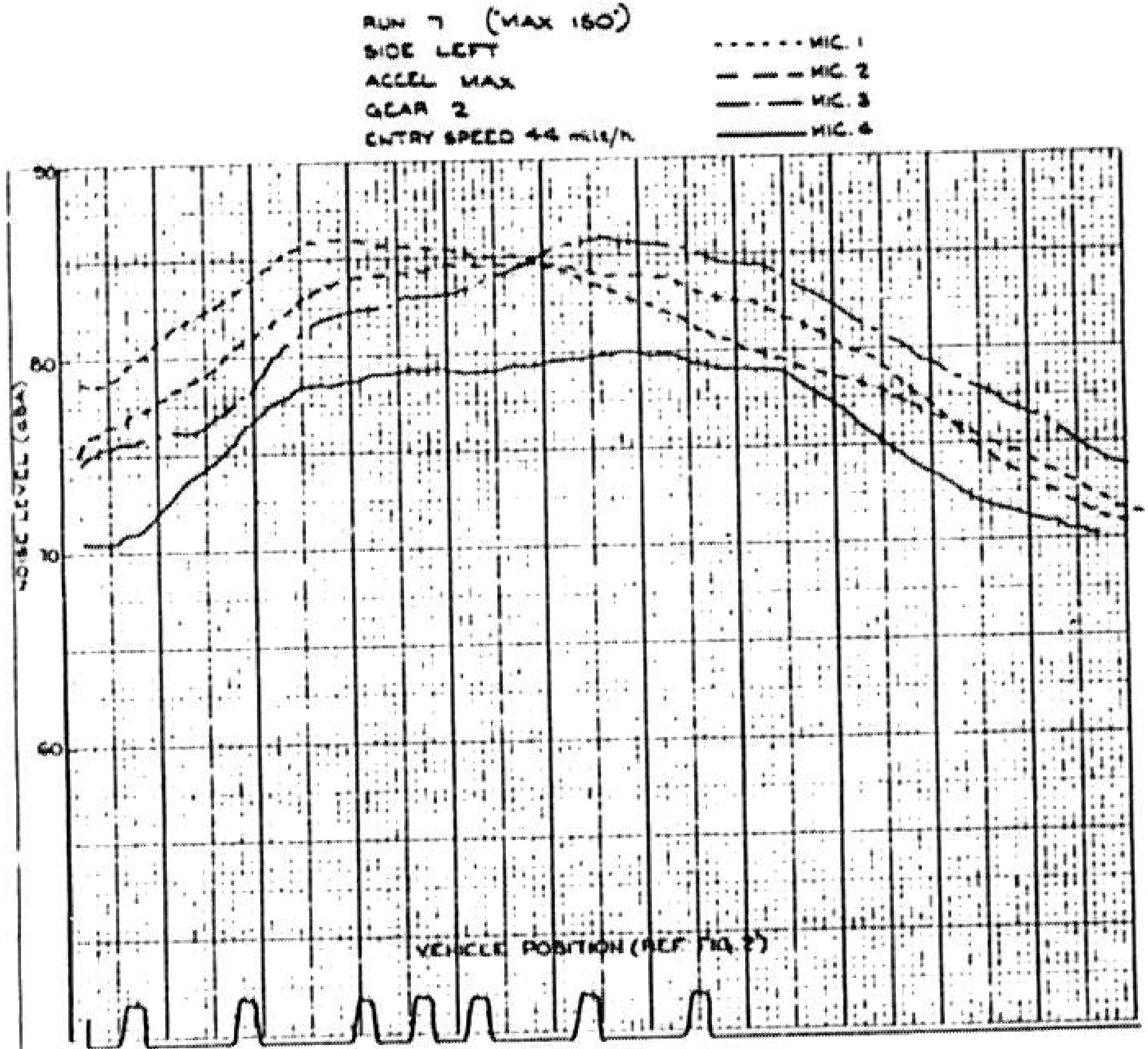


FIGURE 3-44. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - VOLVO 244GL

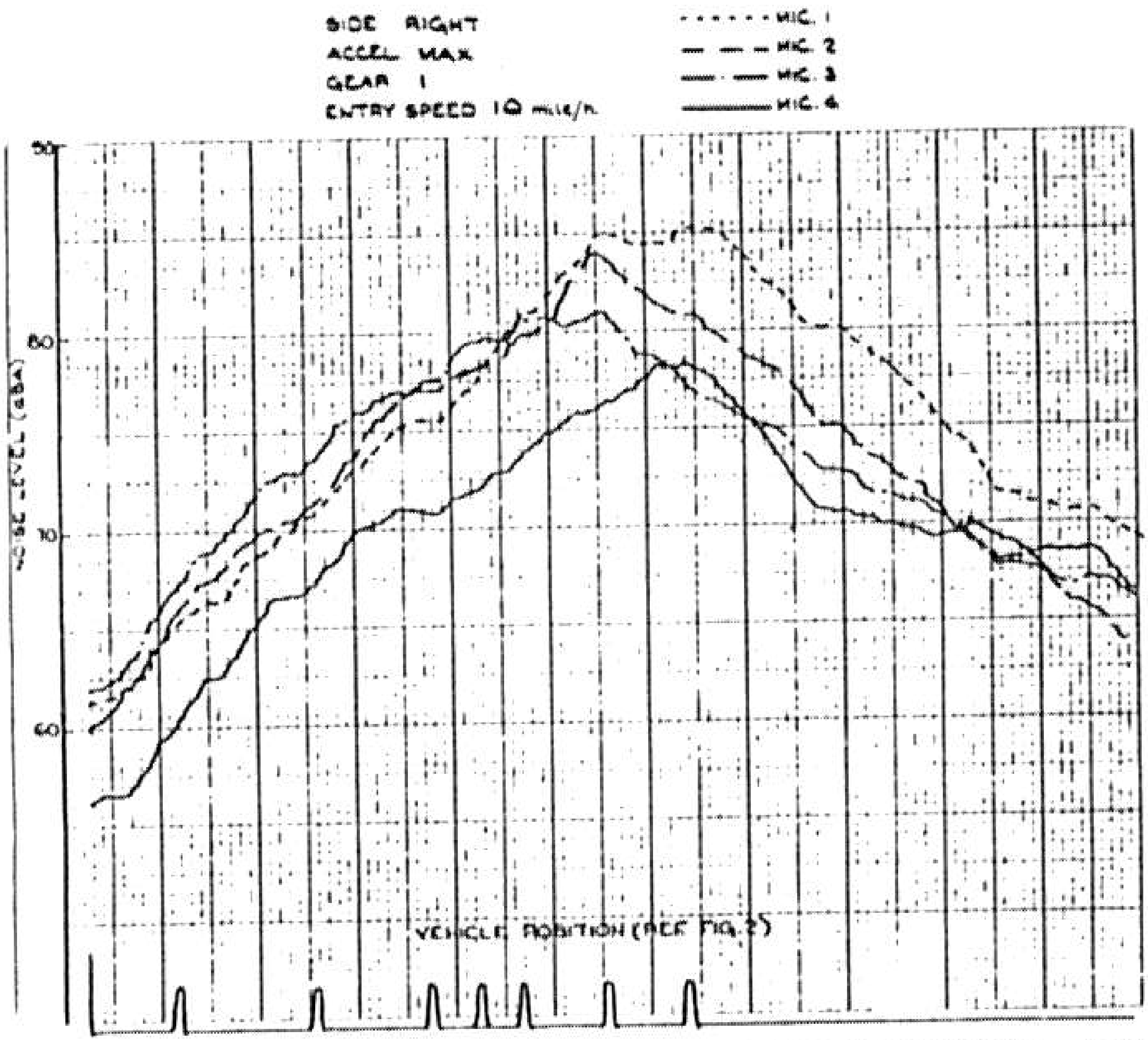


FIGURE 3-45. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - VOLVO 244GL

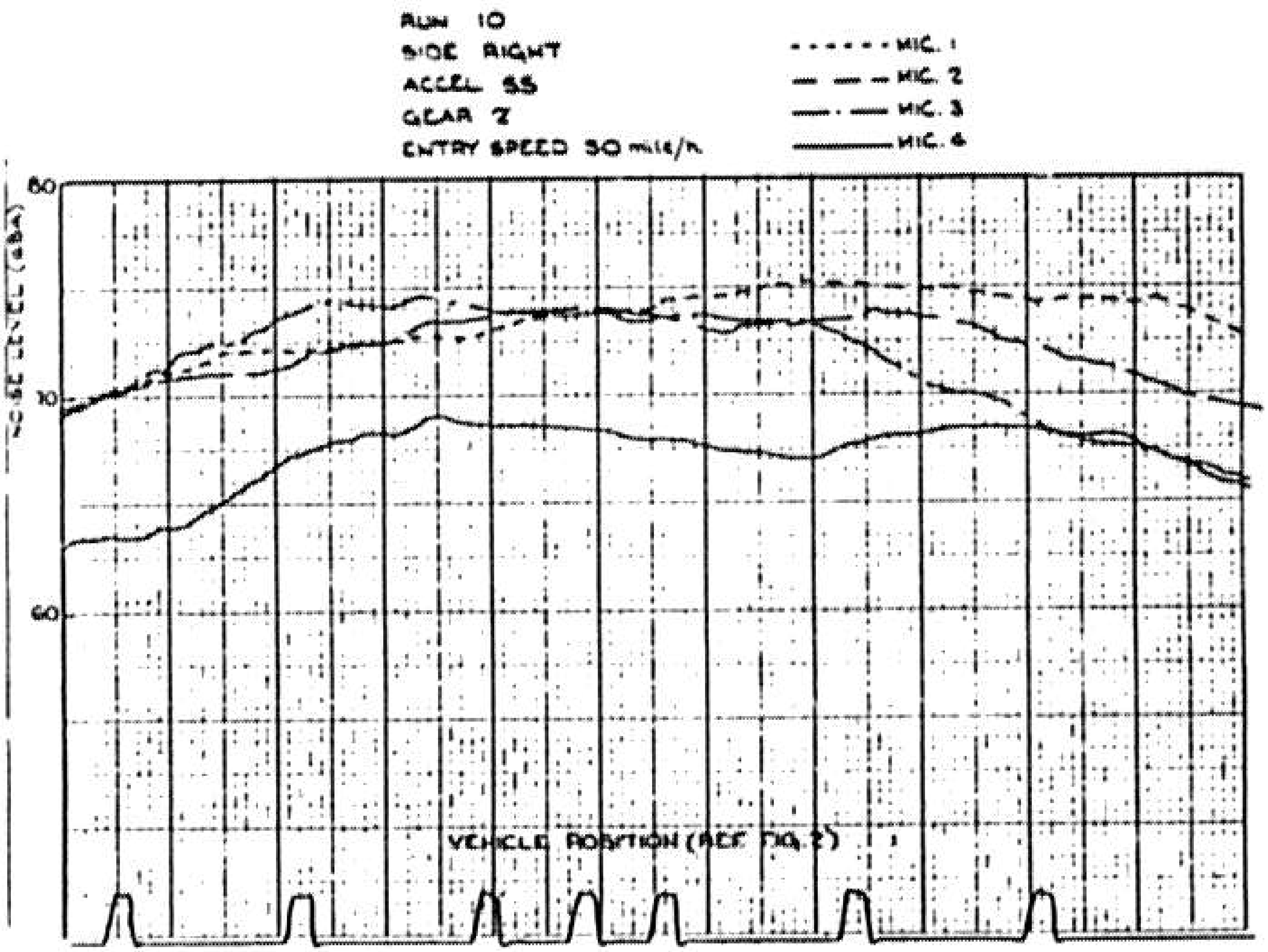


FIGURE 3-46. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - VOLVO 244GL

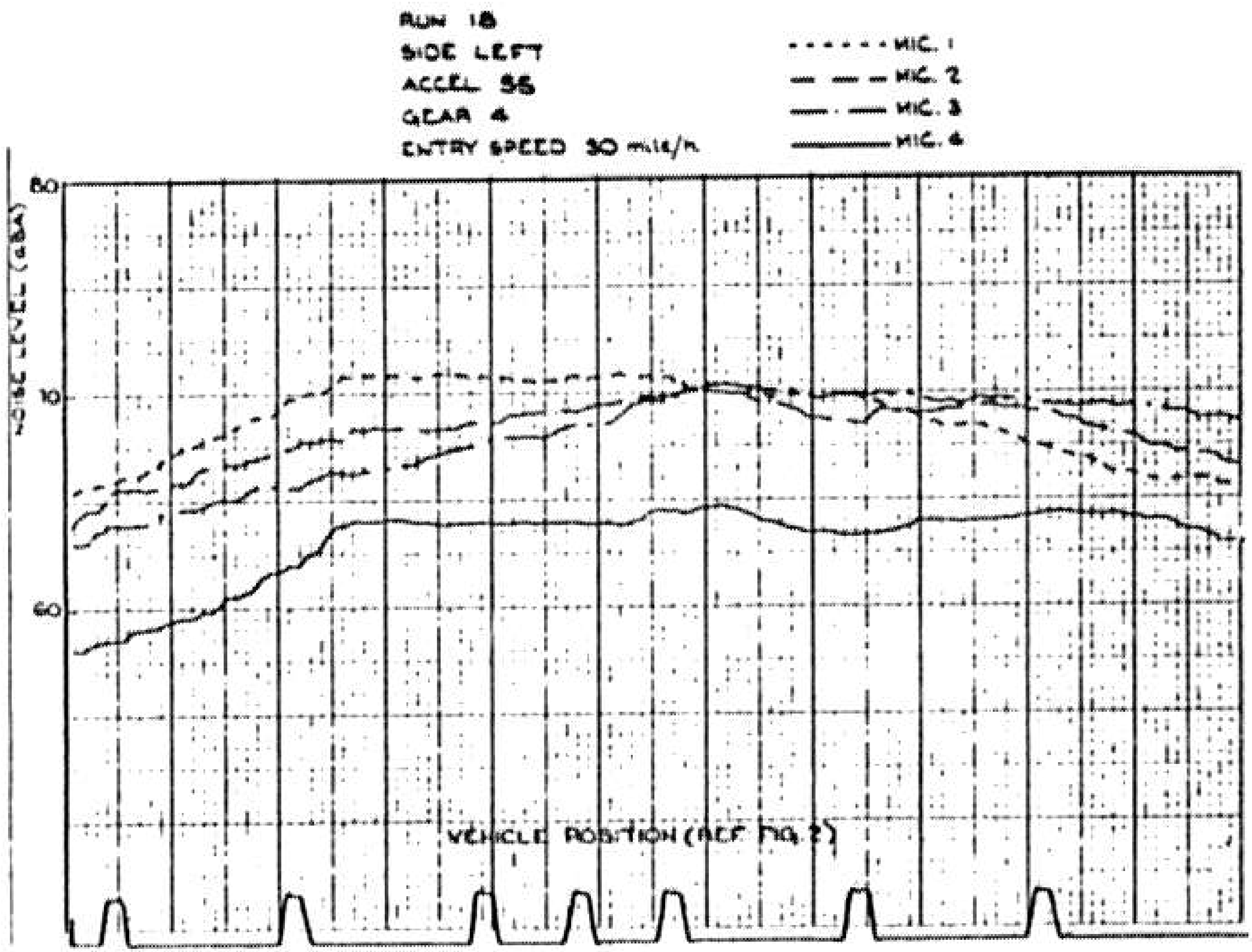


FIGURE 3-47. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - VOLVO 244GL

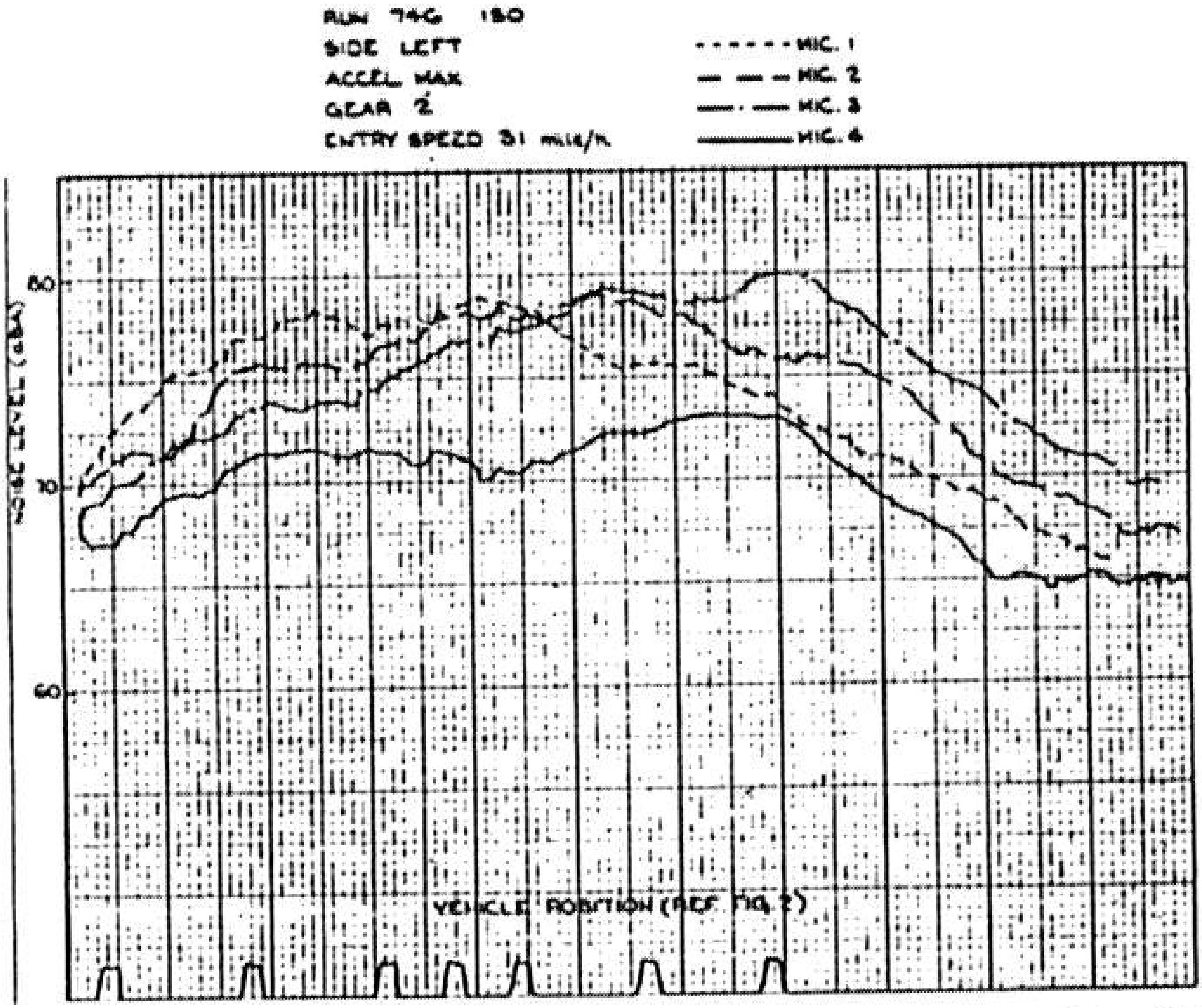


FIGURE 3-48. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - SAAB 99GL INJECTION

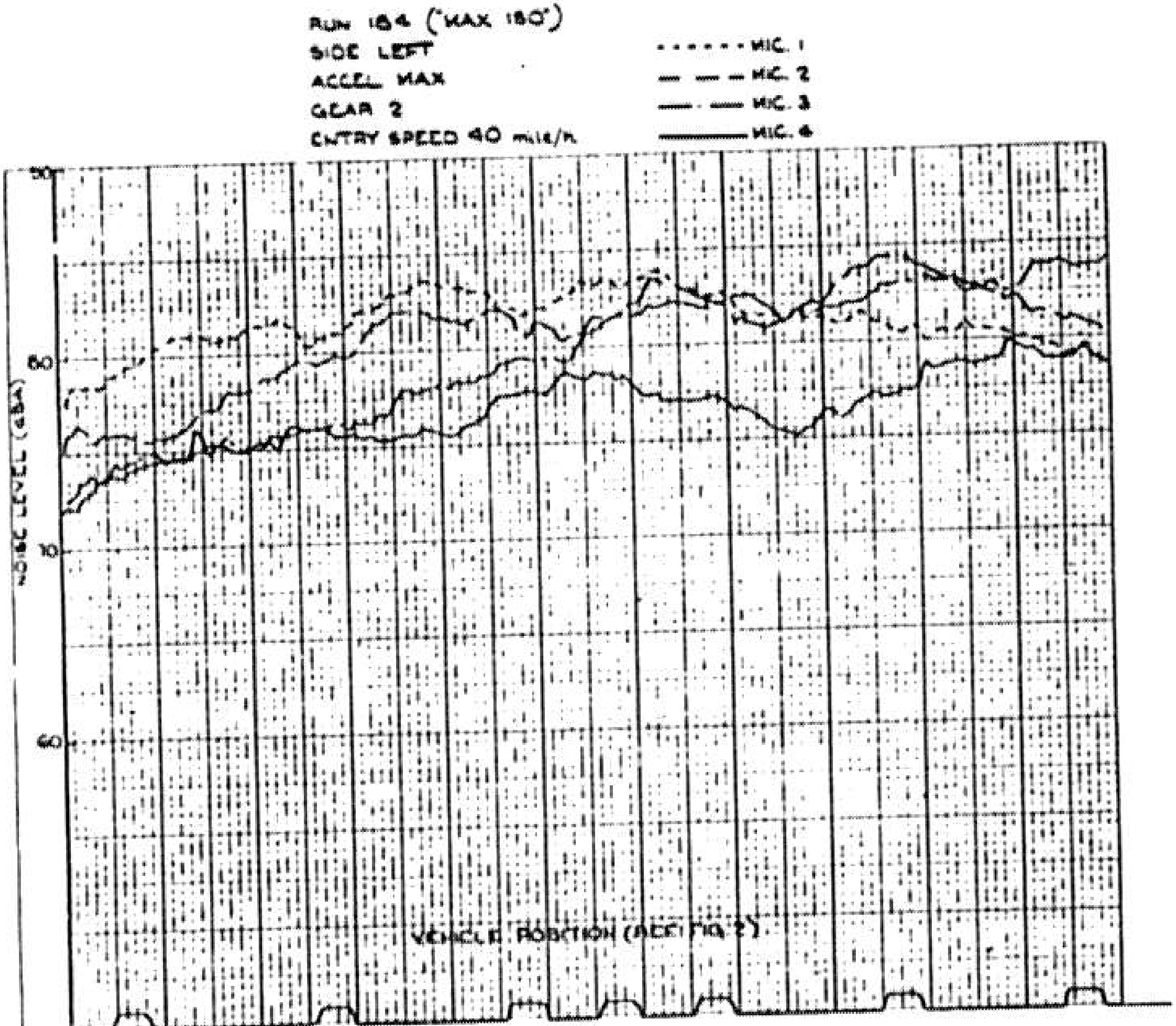


FIGURE 3-49. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - SAAB 99GL INJECTION

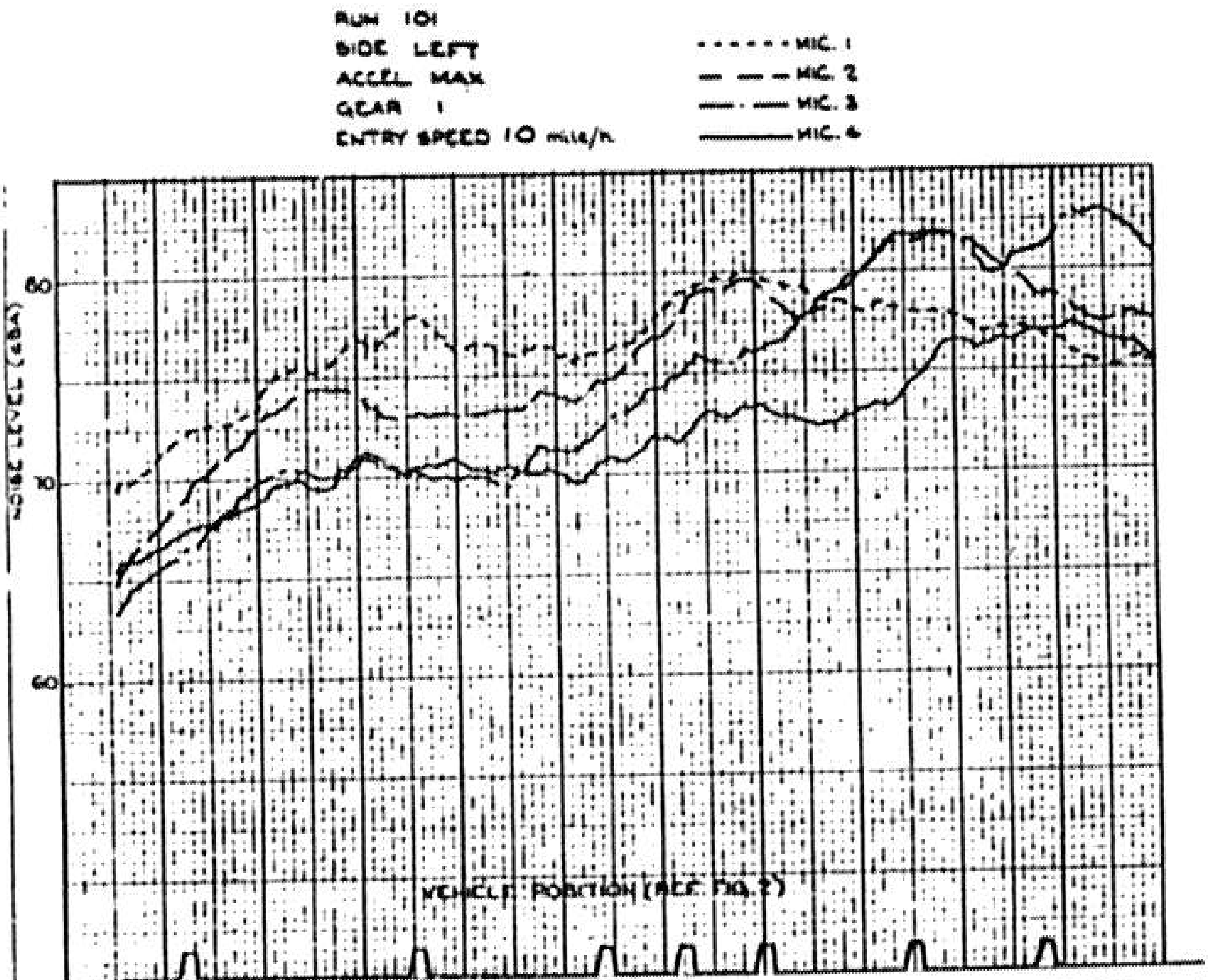


FIGURE 3-50. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - SAAB 99GL

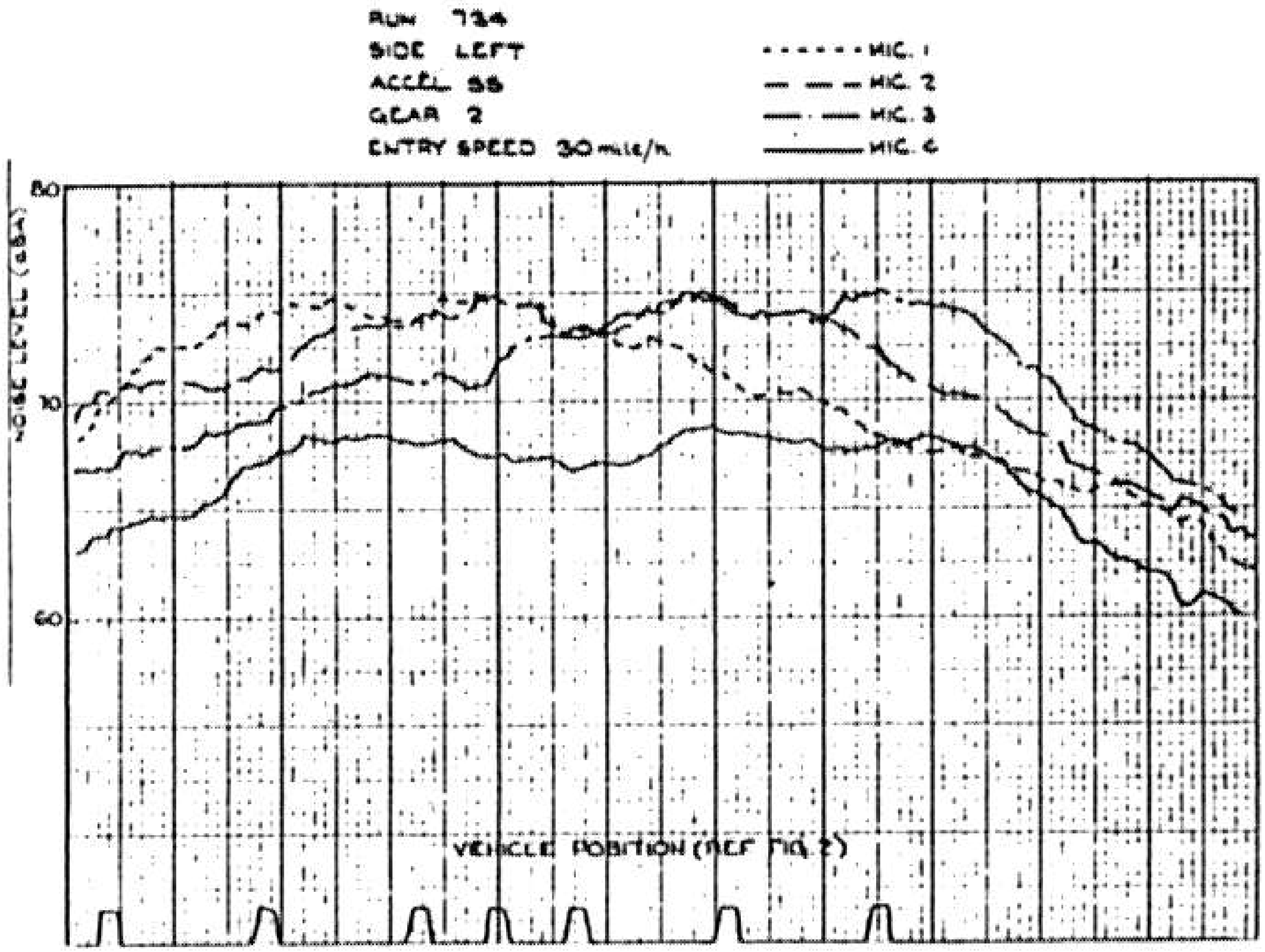


FIGURE 3-51. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - SAAB 99GL

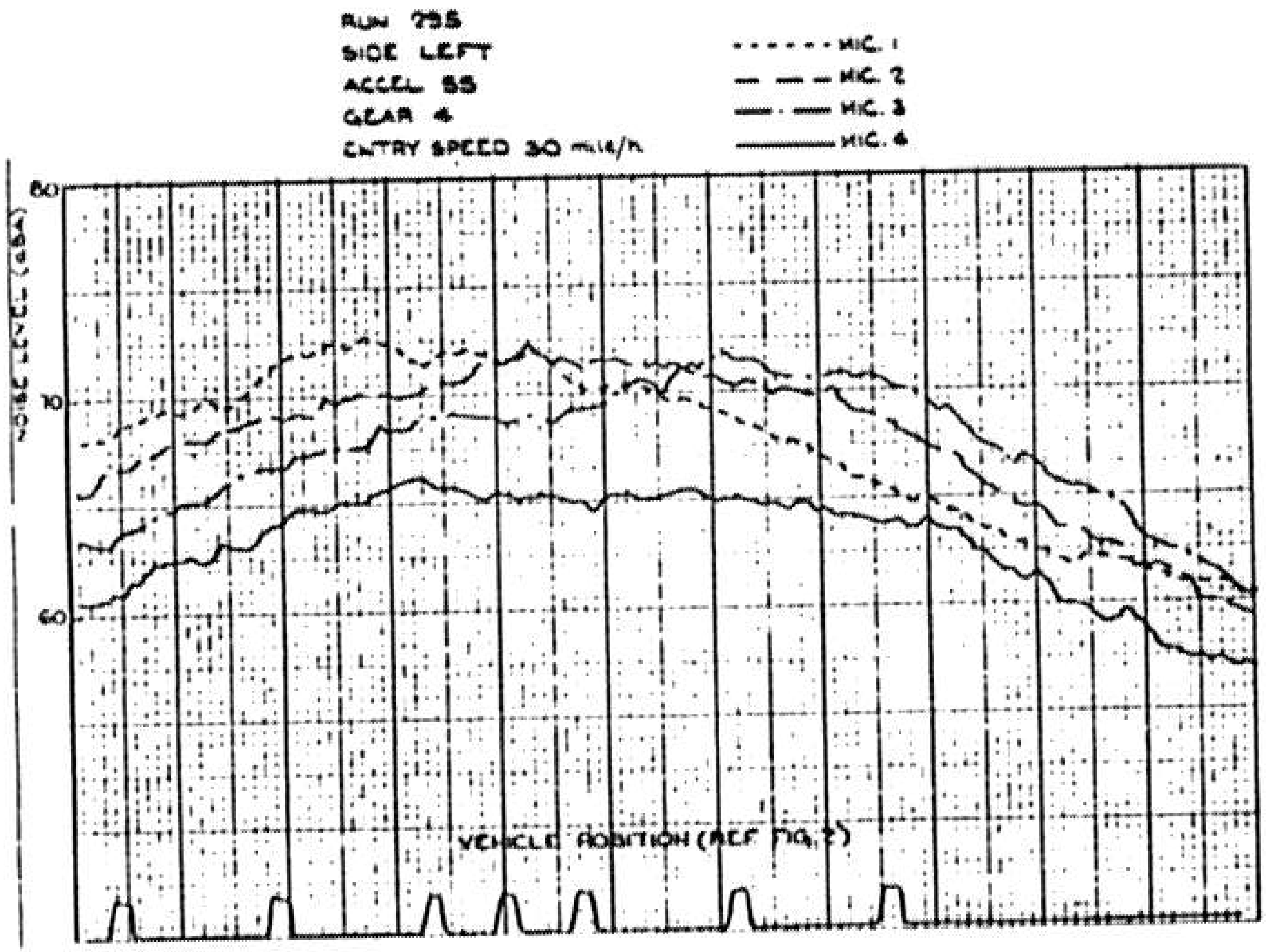


FIGURE 3-52. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - SAAB 99GL

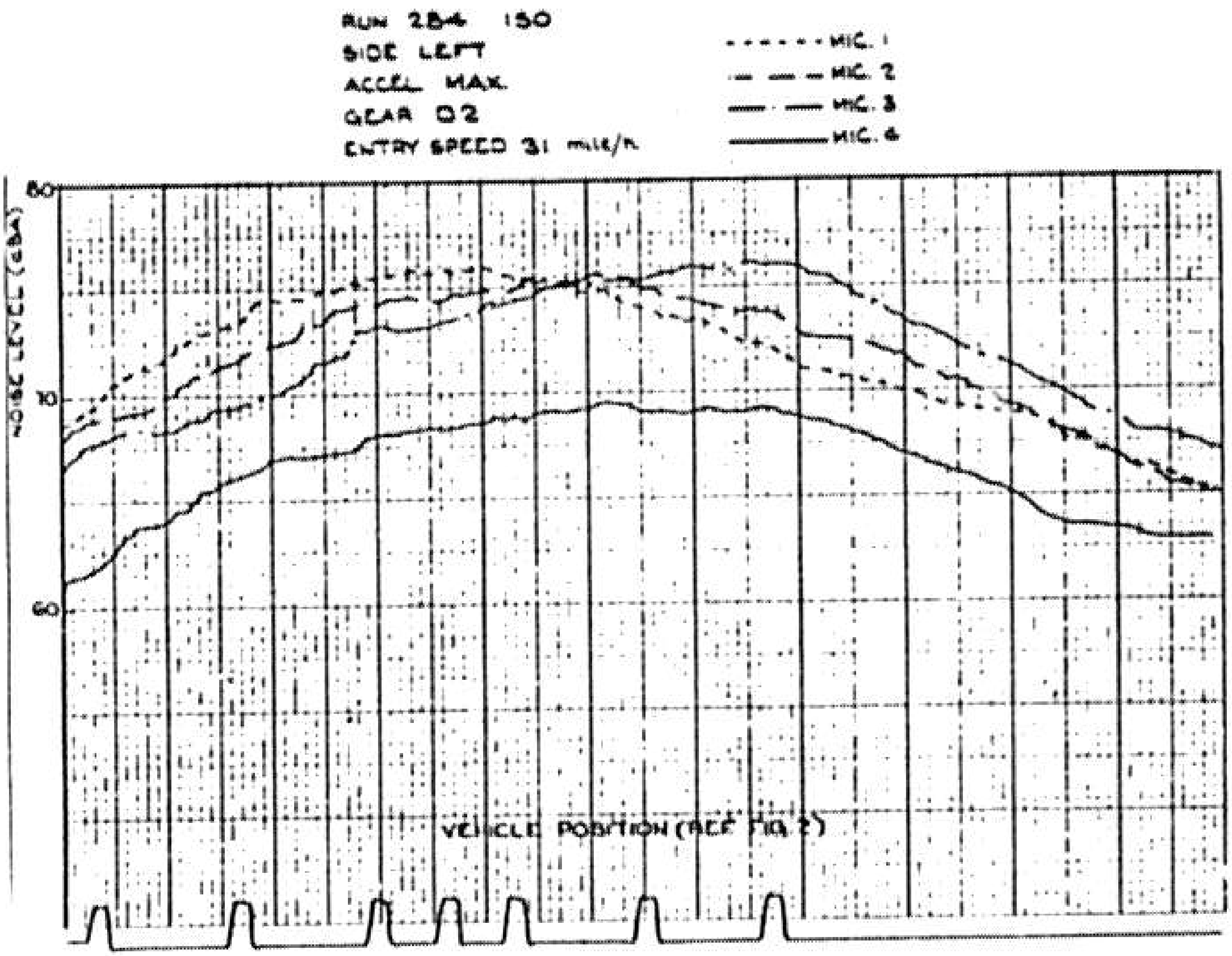


FIGURE 3-53. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DIRVE-BY NOISE TRACES - JAGUAR XJ6

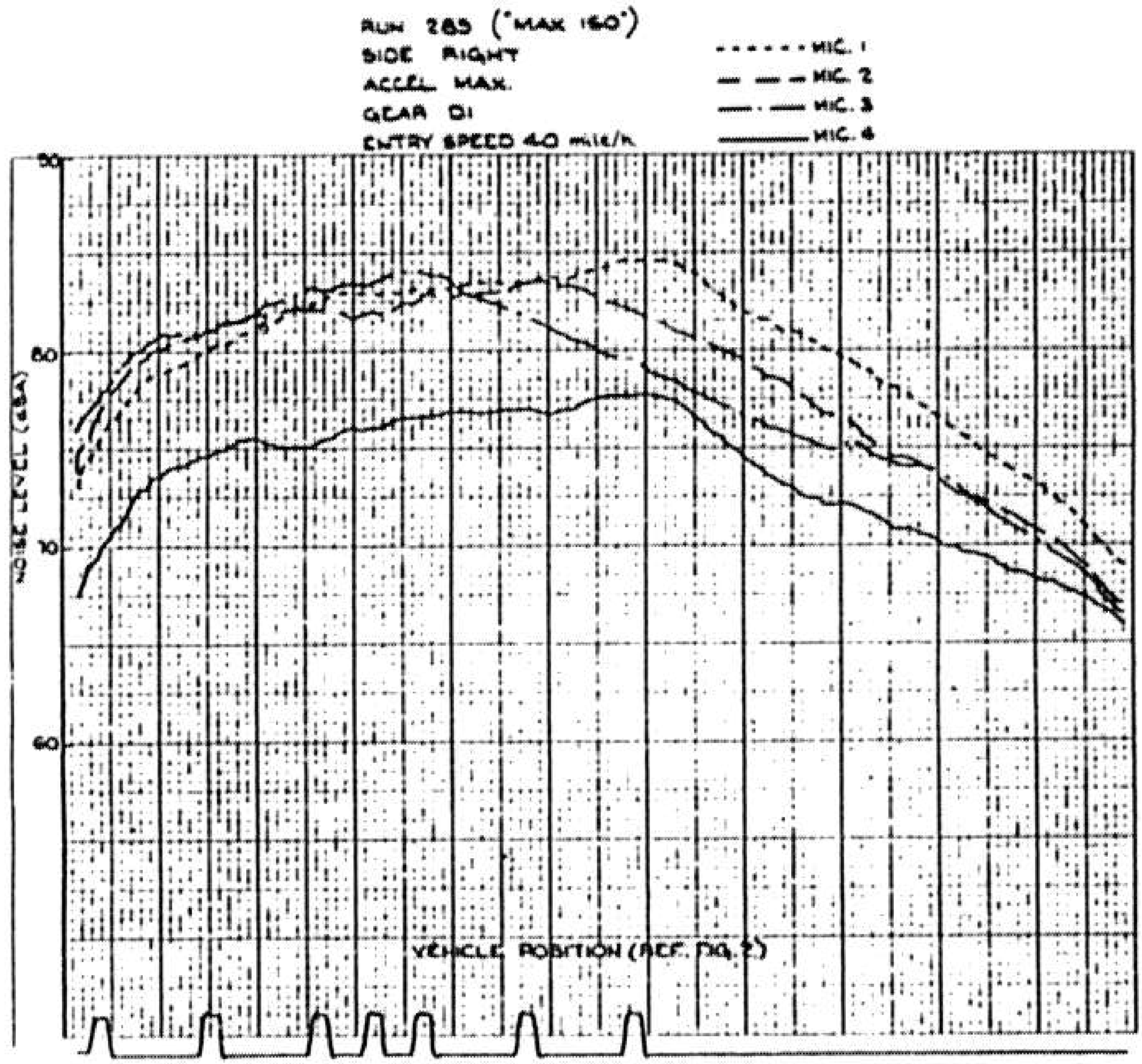


FIGURE 3-54. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - JAGUAR X6J

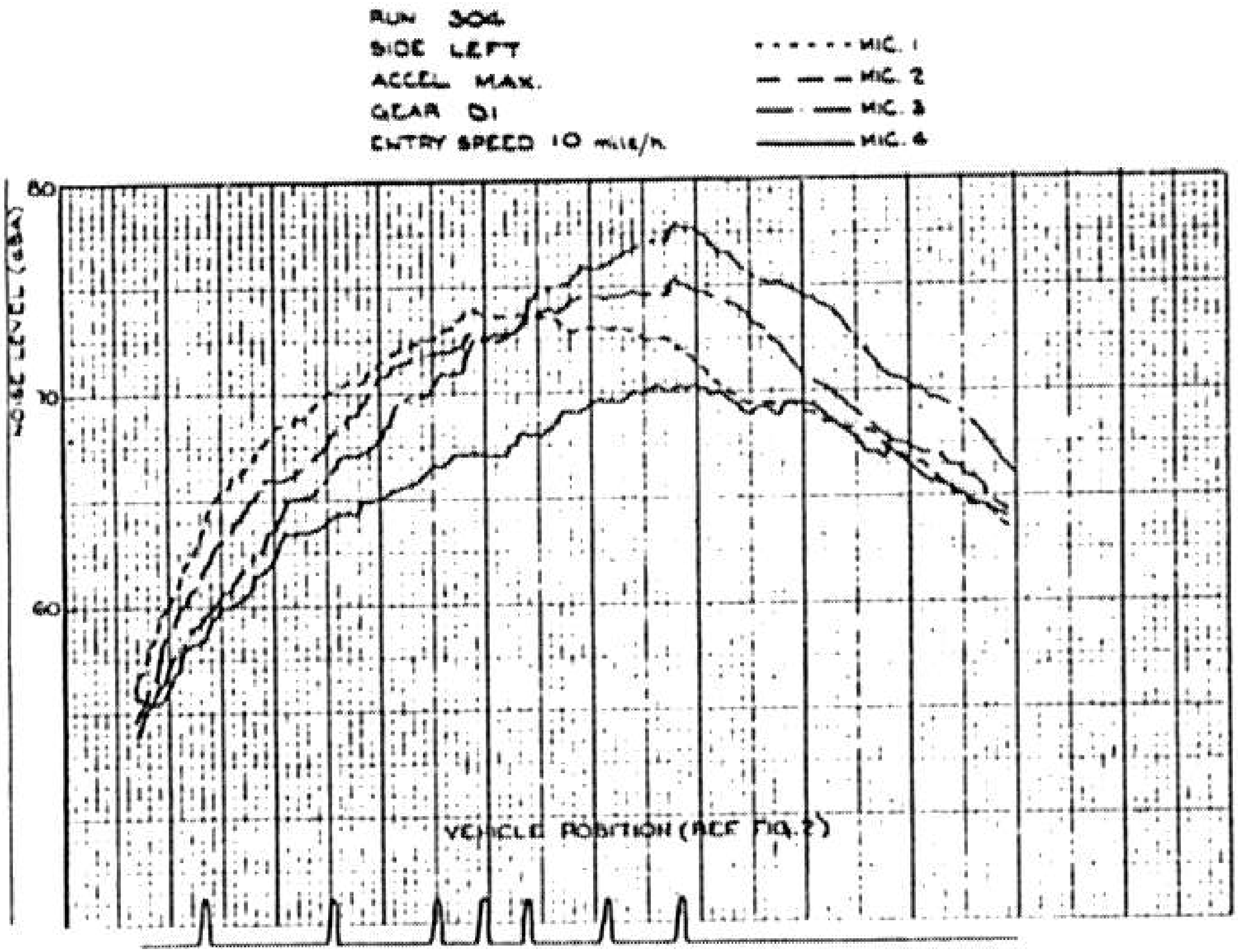


FIGURE 3-55. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - JAGUAR XJ6

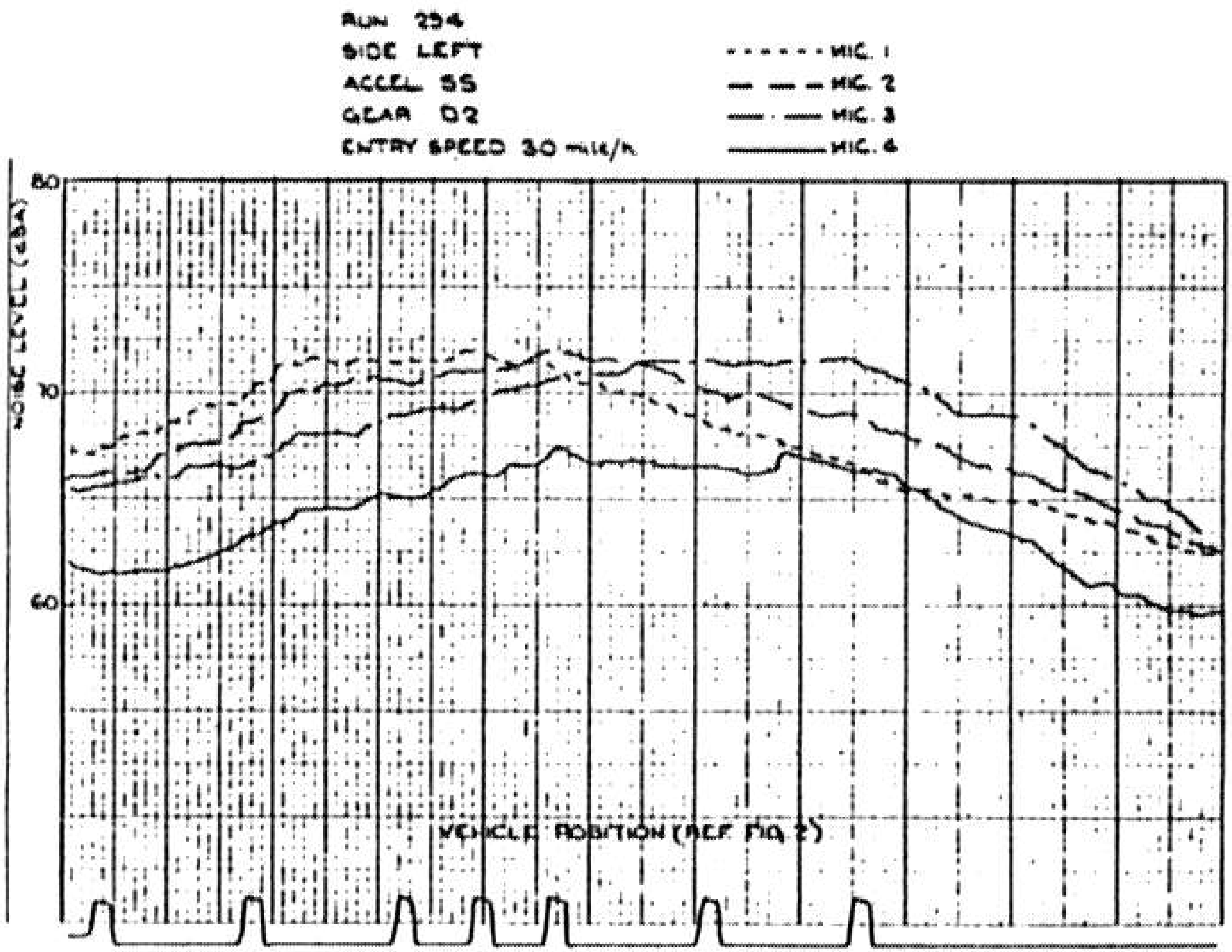


FIGURE 3-56. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - JAGUAR XJ6

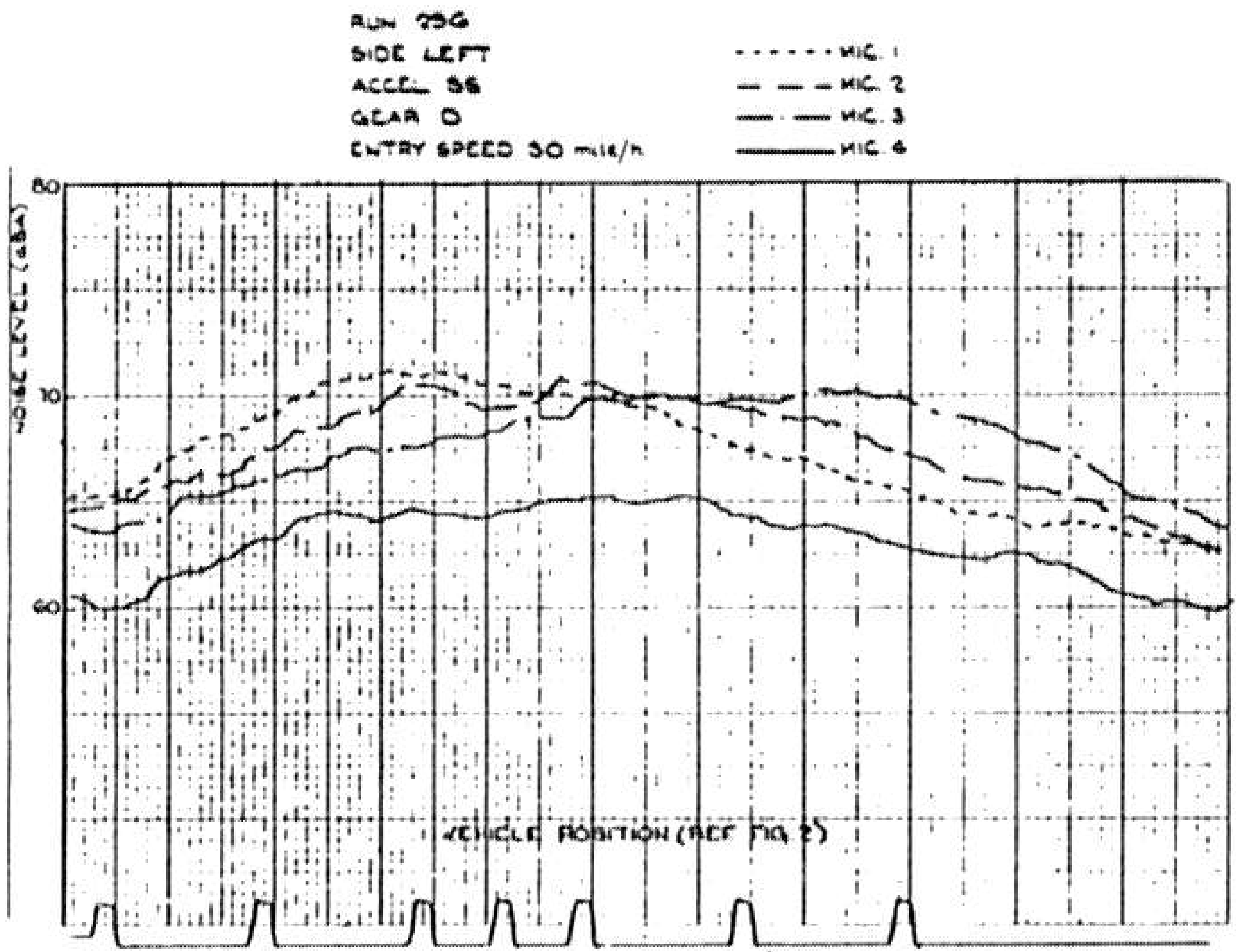


FIGURE 3-57. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - JAGUAR XJ6

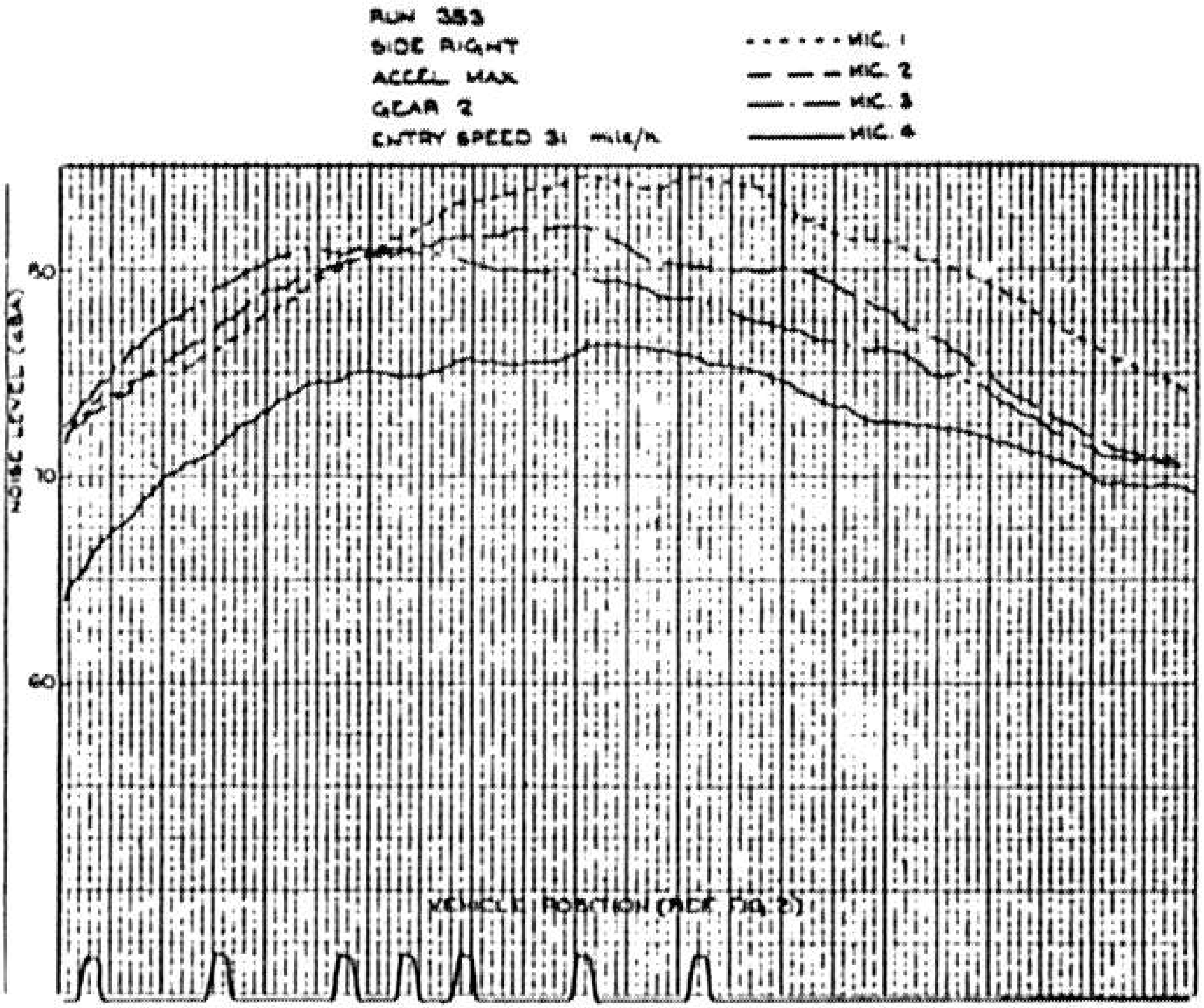


FIGURE 3-58. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - DOLOMITE SPRINT

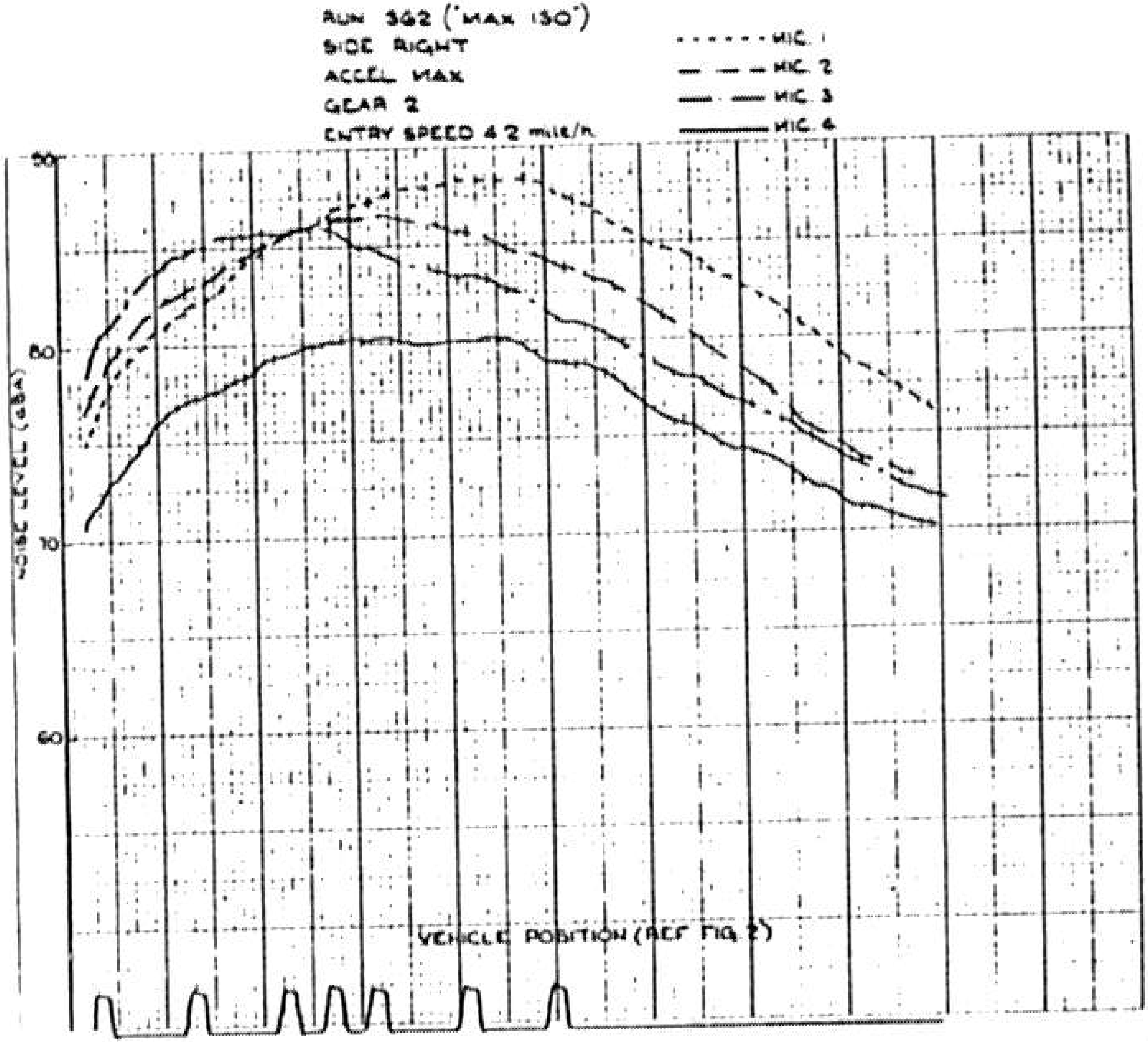


FIGURE 3-59. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - DOLOMITE SPRINT

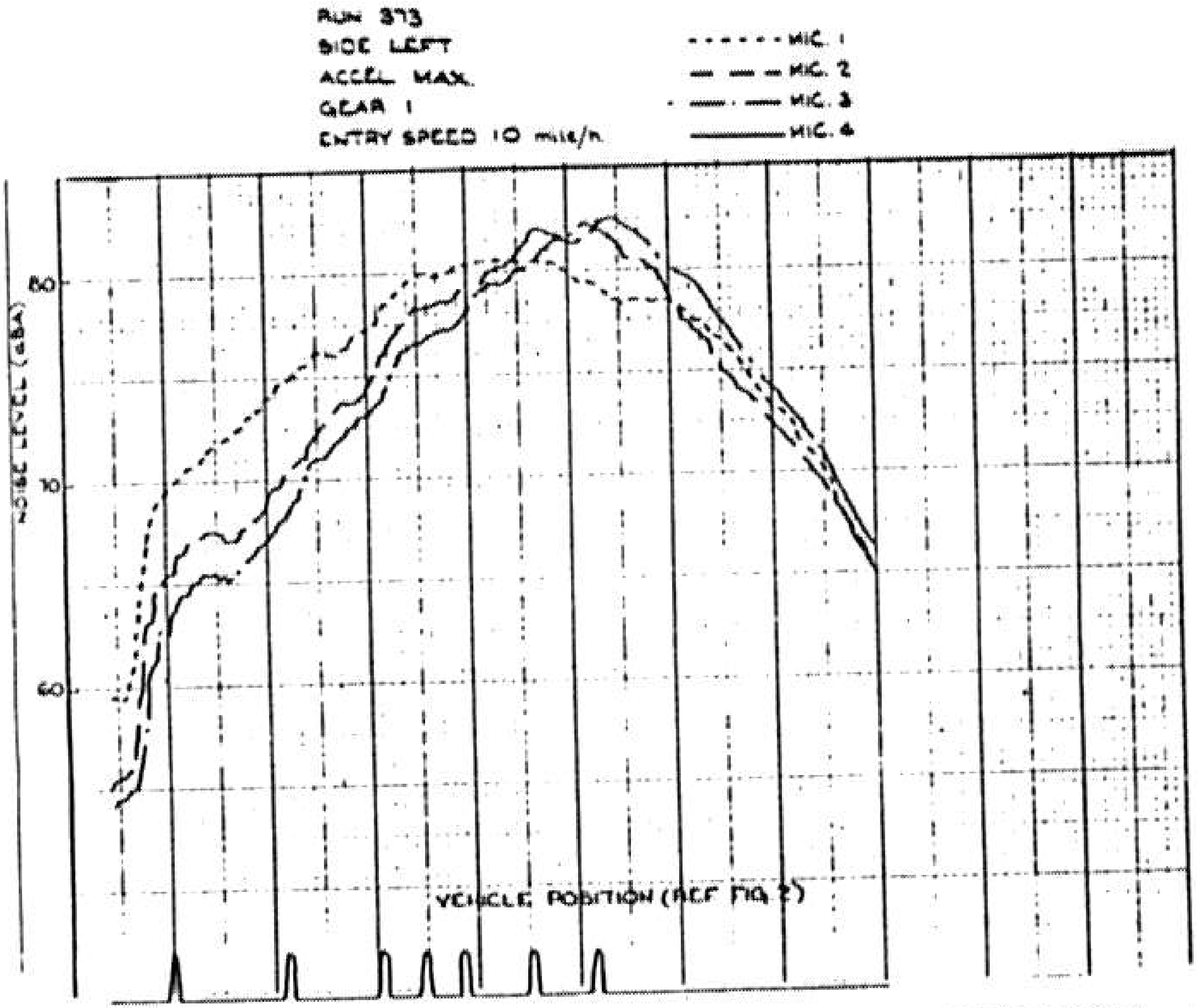


FIGURE 3-60. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - DOLOMITE SPRINT

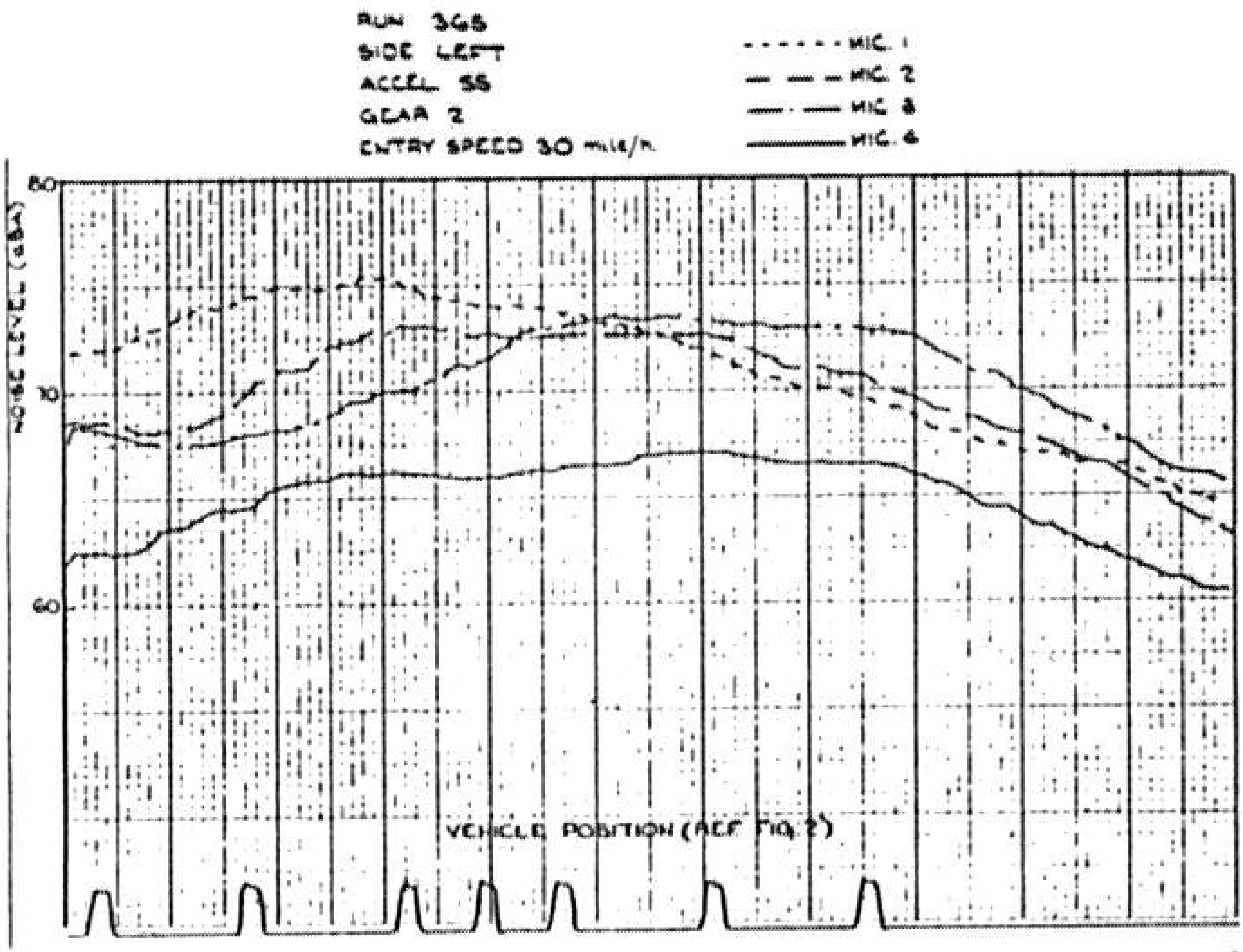


FIGURE 3-61. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - DOLOMITE SPRINT

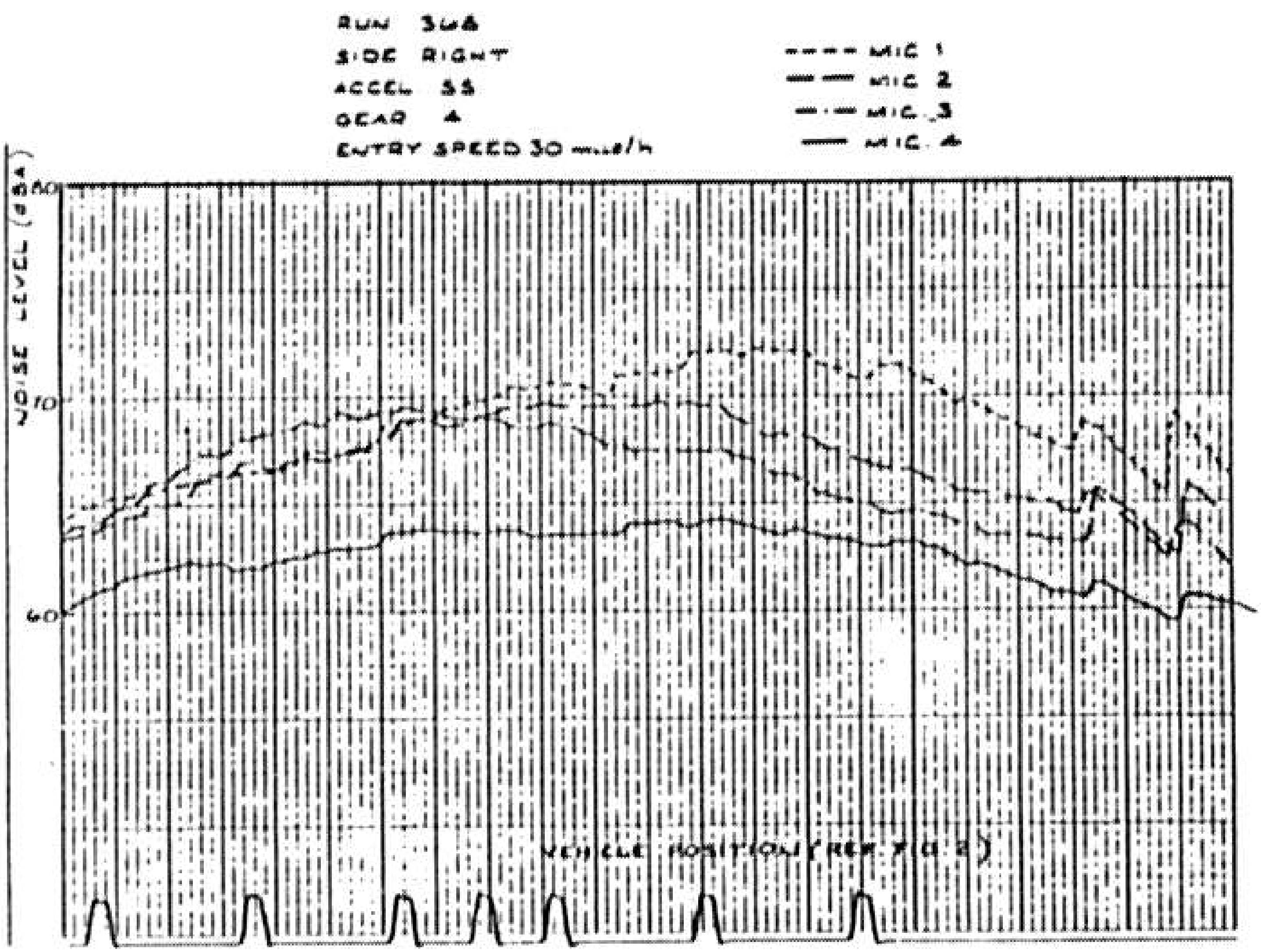


FIGURE 3-62. CALSPAN/DOT HIGH SPEED ENGINES PROJECT DRIVE-BY NOISE TRACES - DOLOMITE SPRINT

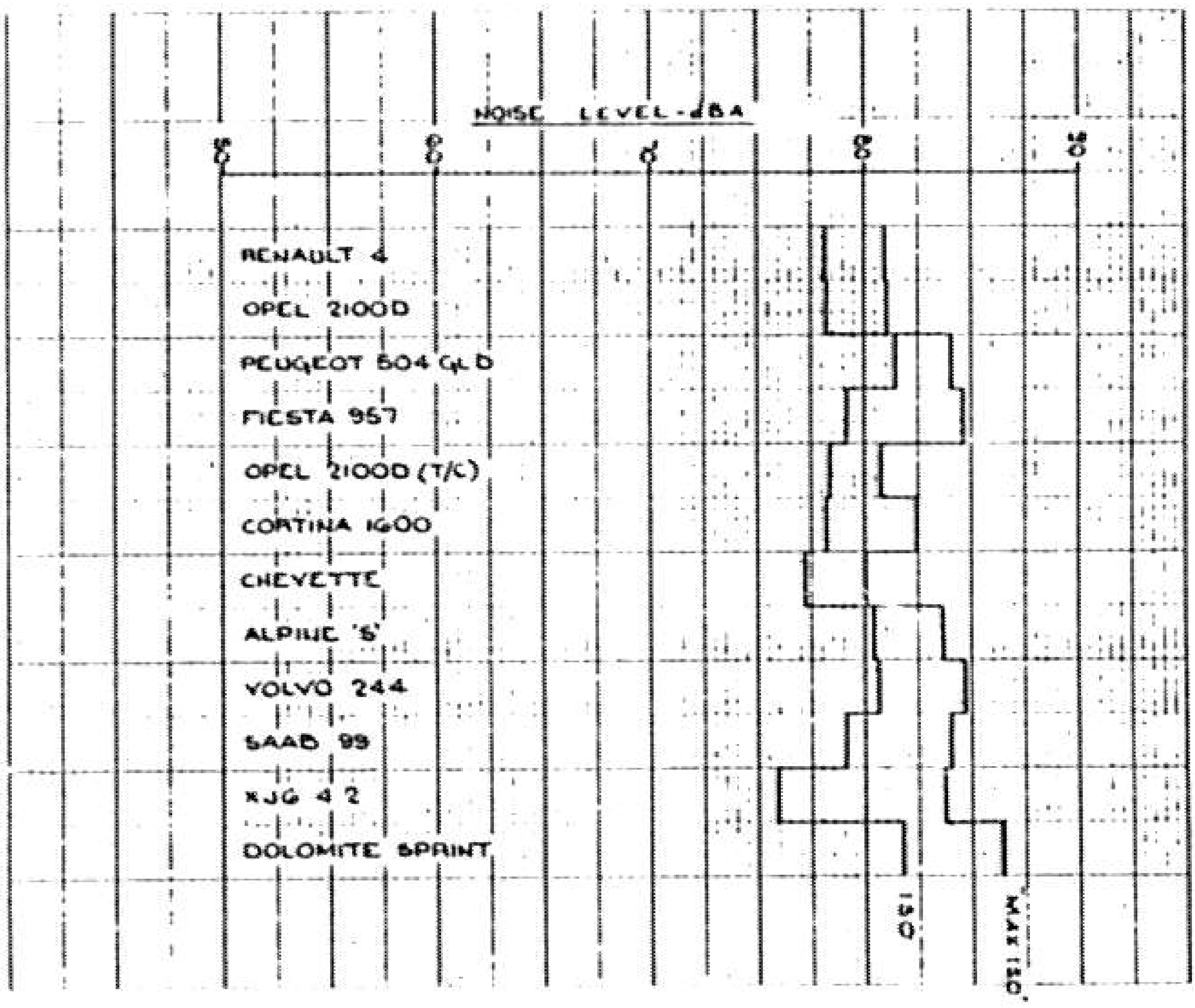


FIGURE 3-63. I.S.O. DRIVE BY TESTS ON ADDITIONAL VEHICLES
I.S.O. AND "MAX I.S.O." TESTS IN 2ND GEAR

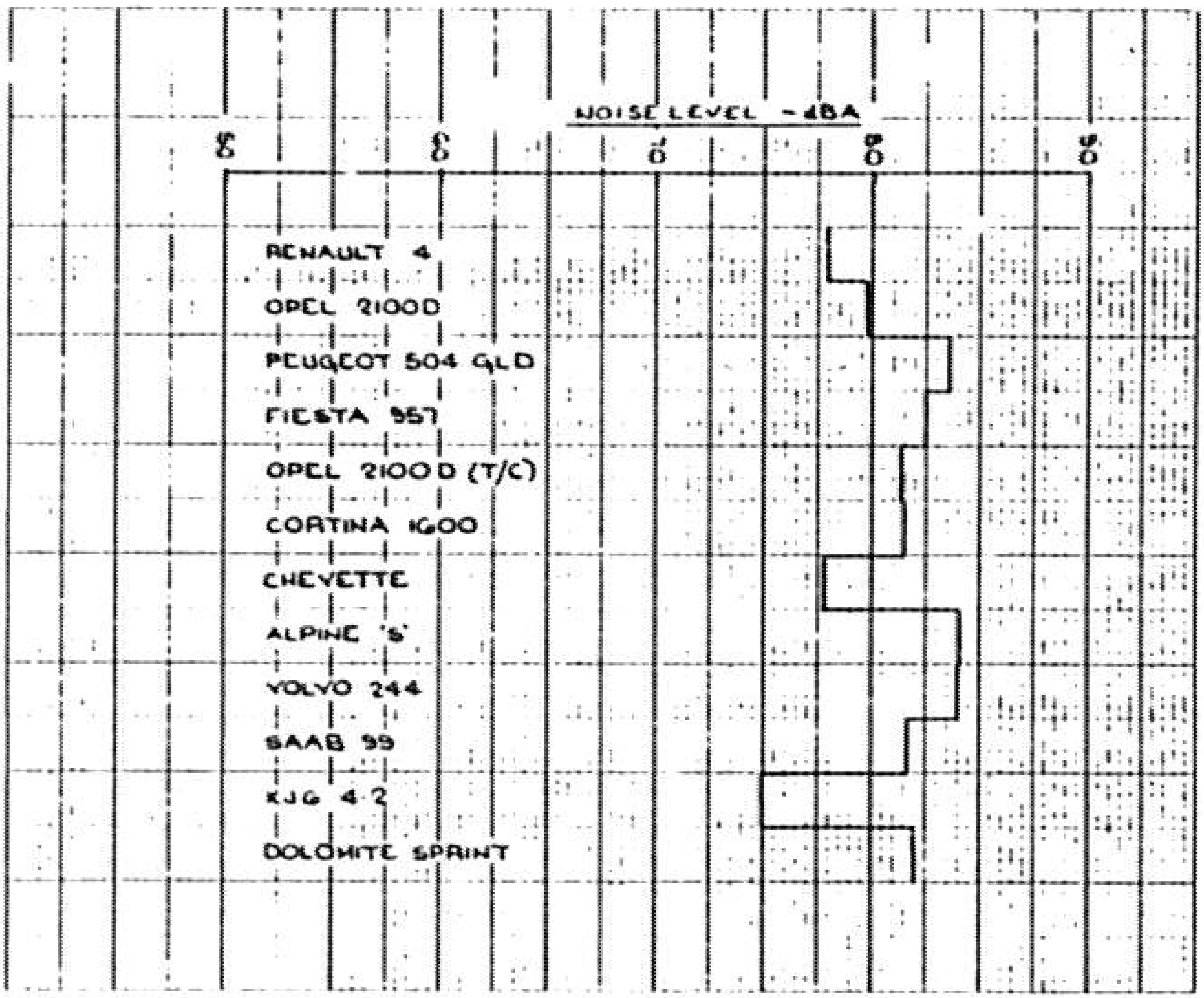


FIGURE 3-64. ADDITIONAL VEHICLE NOISE TESTS-MAXIMUM ACCELERATION FROM 10 MILE/H IN 1ST GEAR

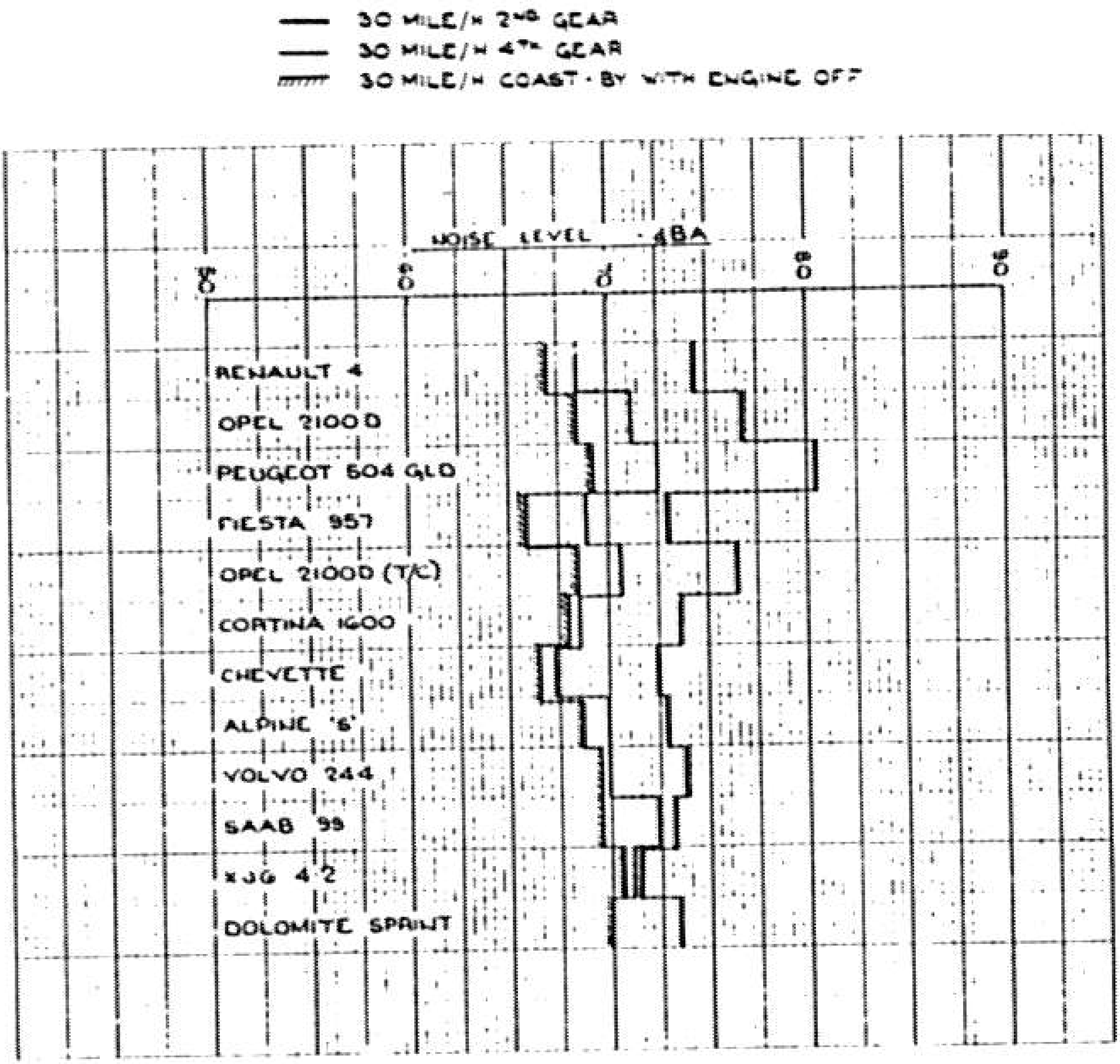


FIGURE 3-65. STEADY STATE DRIVE-BY TESTS ON ADDITIONAL VEHICLES AT 30 MILE/H STEADY STATE

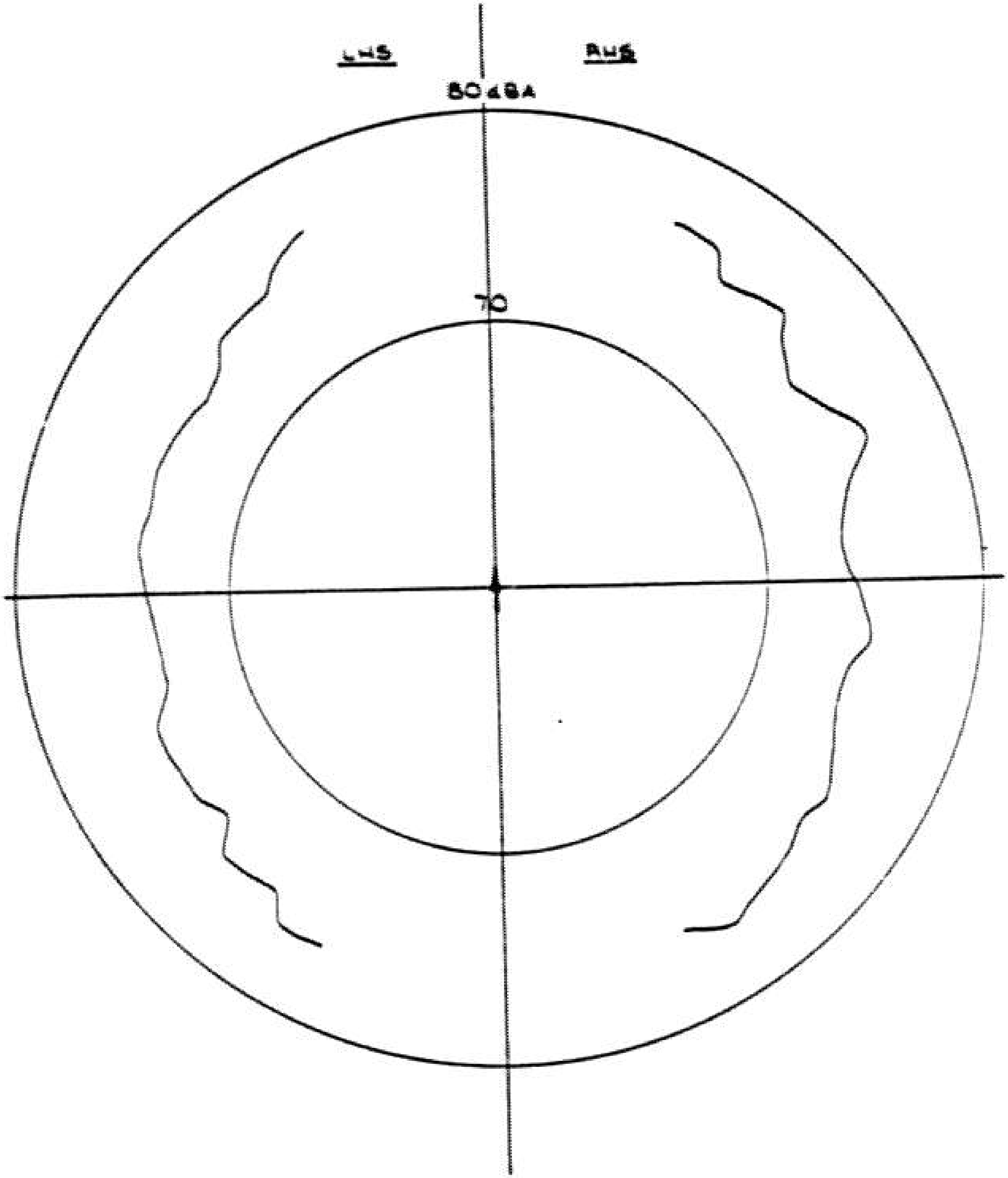


FIGURE 3-66. POLAR PLOT OF NOISE DISTRIBUTION
RENAULT 4 30 MILE/H, 2ND GEAR

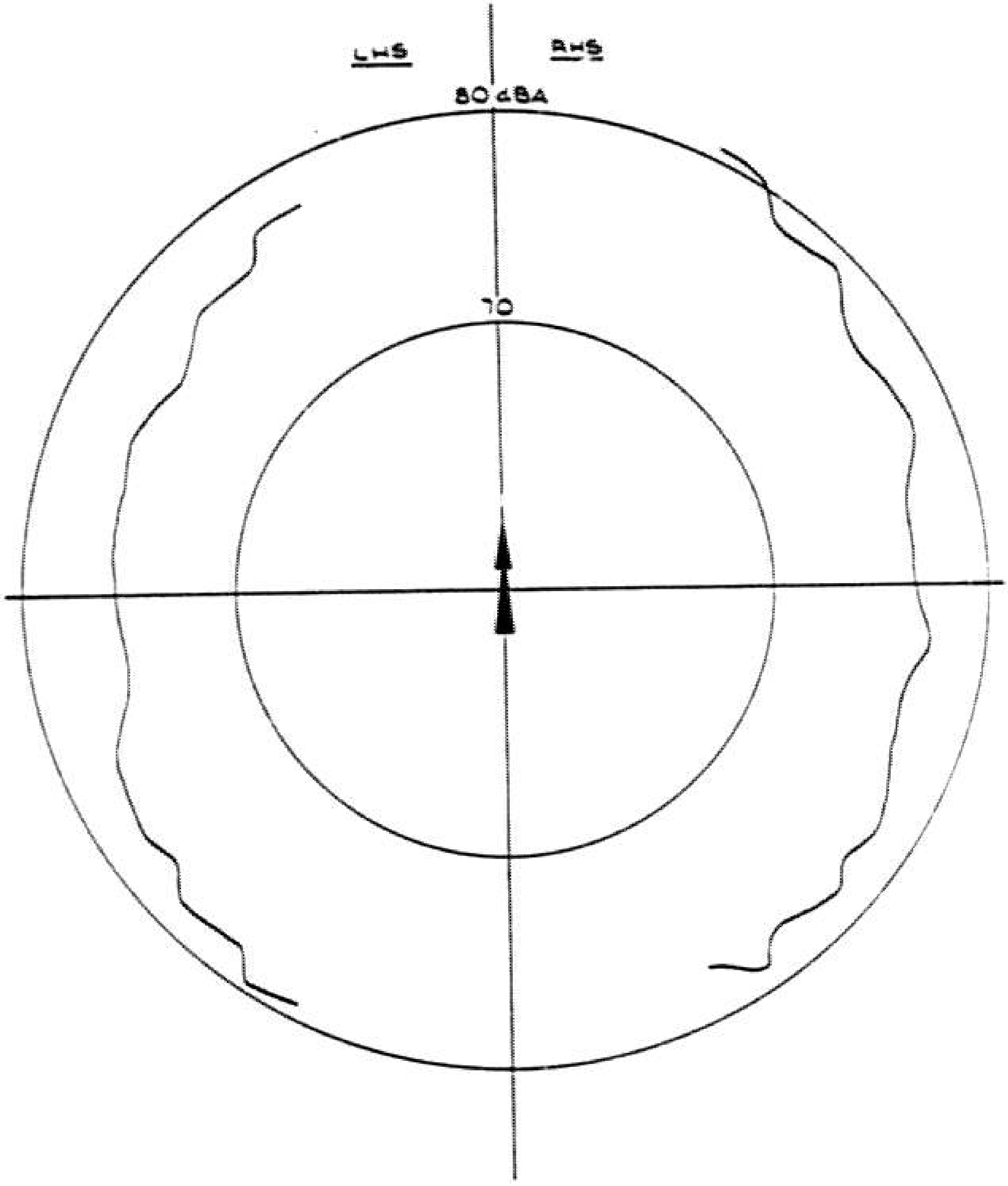


FIGURE 3-67. POLAR PLOT OF NOISE DISTRIBUTION
OPEL 2100D 30 MILE/H, 2ND GEAR

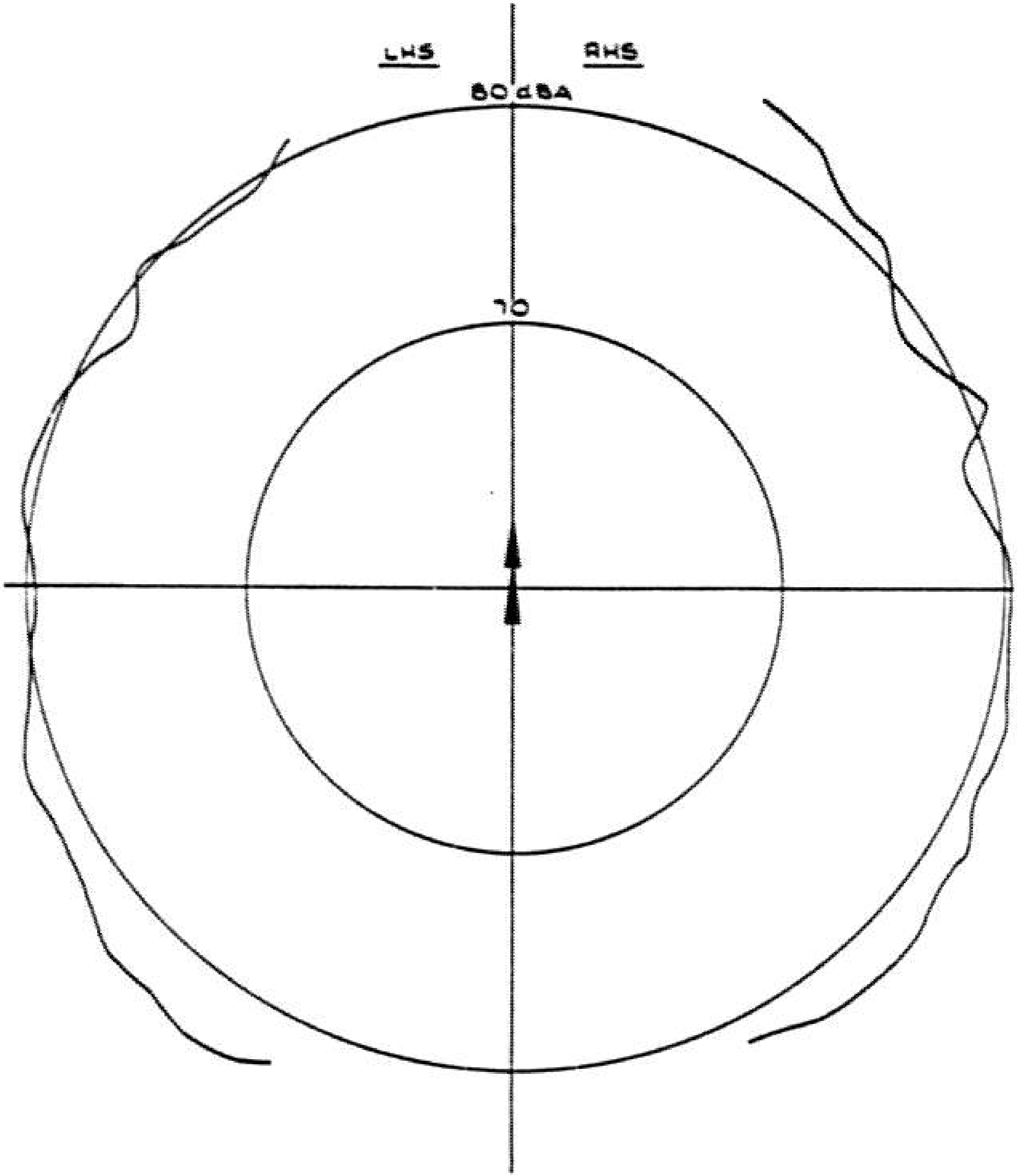


FIGURE 3-68. POLAR PLOT OF NOISE DISTRIBUTION
PEUGEOT 504 GLD, 30 MILE/H, 2ND GEAR

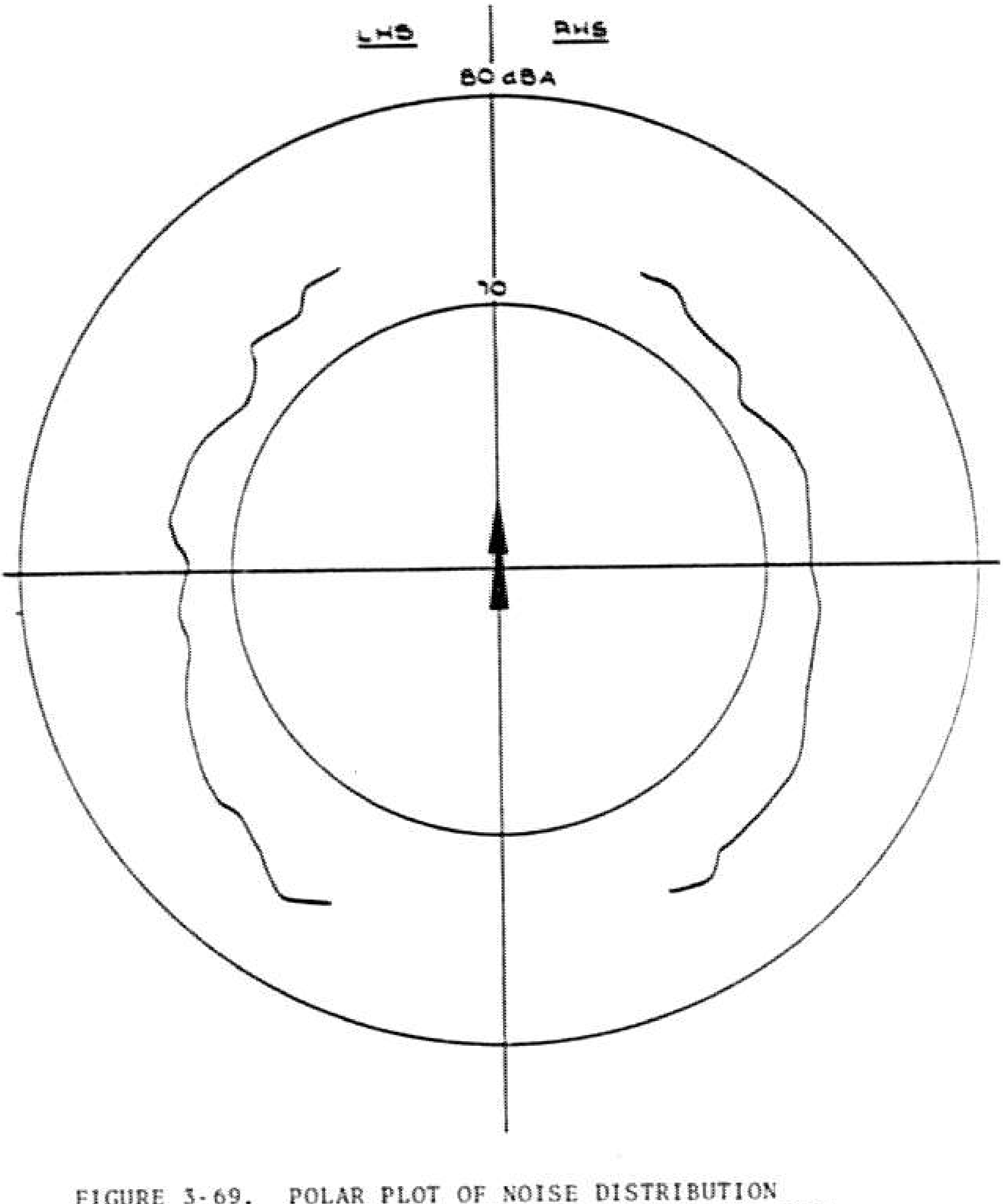


FIGURE 3-69. POLAR PLOT OF NOISE DISTRIBUTION
FORD FIESTA 957, 30 MILE/H, 2ND GEAR

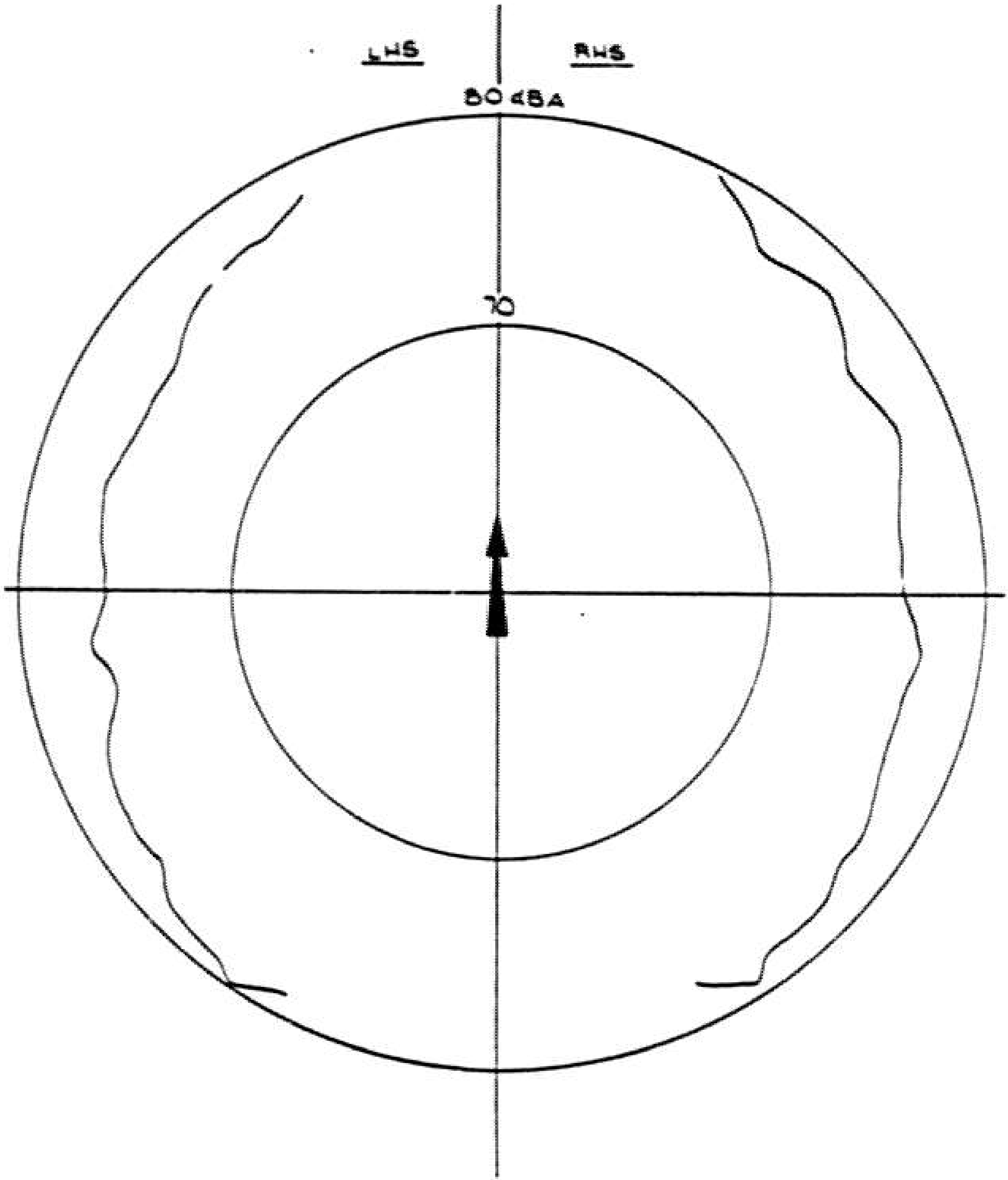


FIGURE 3-70. POLAR PLOT OF NOISE DISTRIBUTION
OPEL 2100D T/C, 30 MILE/H, 2ND GEAR

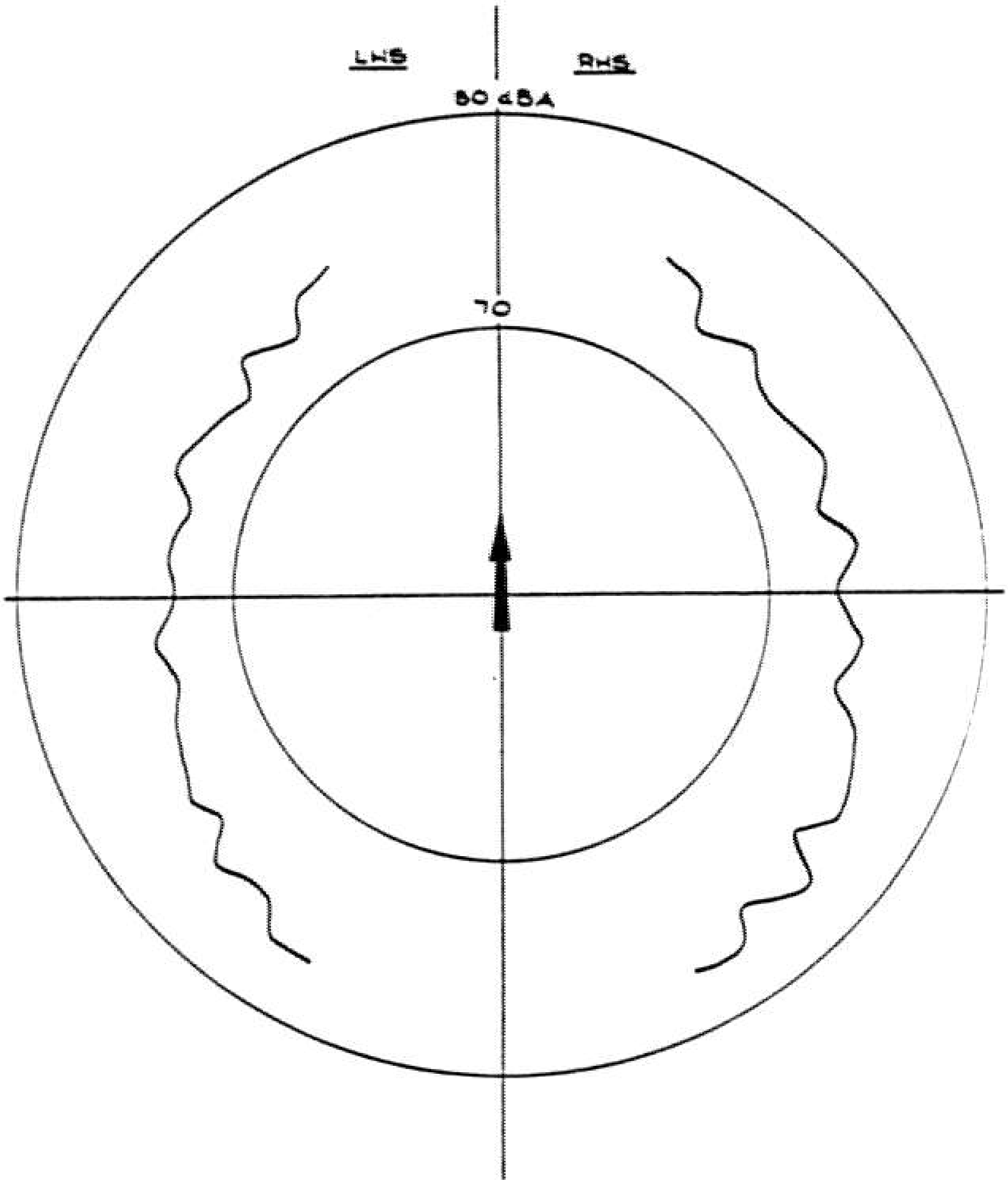


FIGURE 3-71. POLAR PLOT OF NOISE DISTRIBUTION
FORD CORTINA 1600, 30 MILE/H, 2ND GEAR

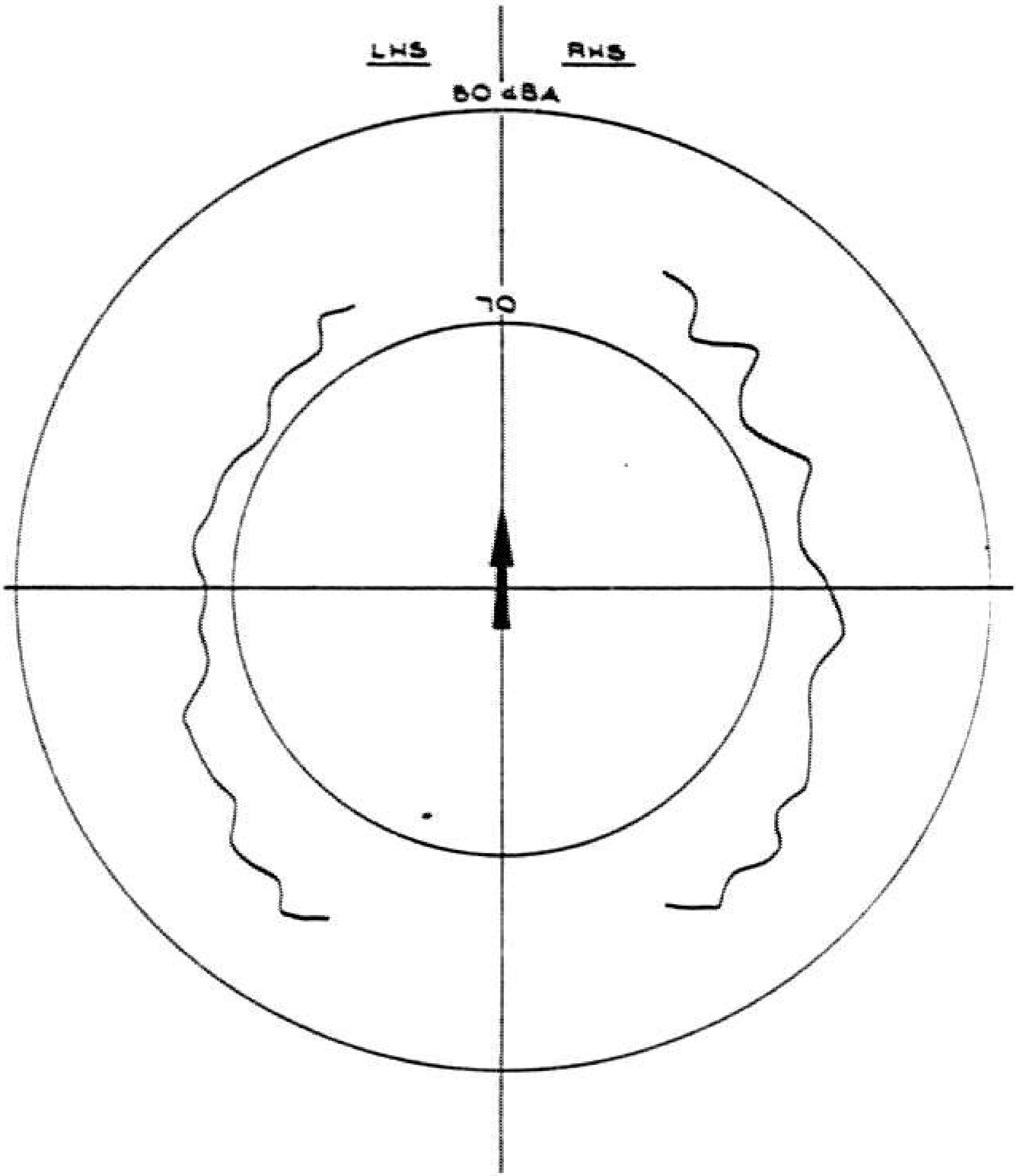


FIGURE 3-72. POLAR PLOT OF NOISE DISTRIBUTION
VAUXHALL CHEVETTE, 30 MILE/H, 2ND GEAR

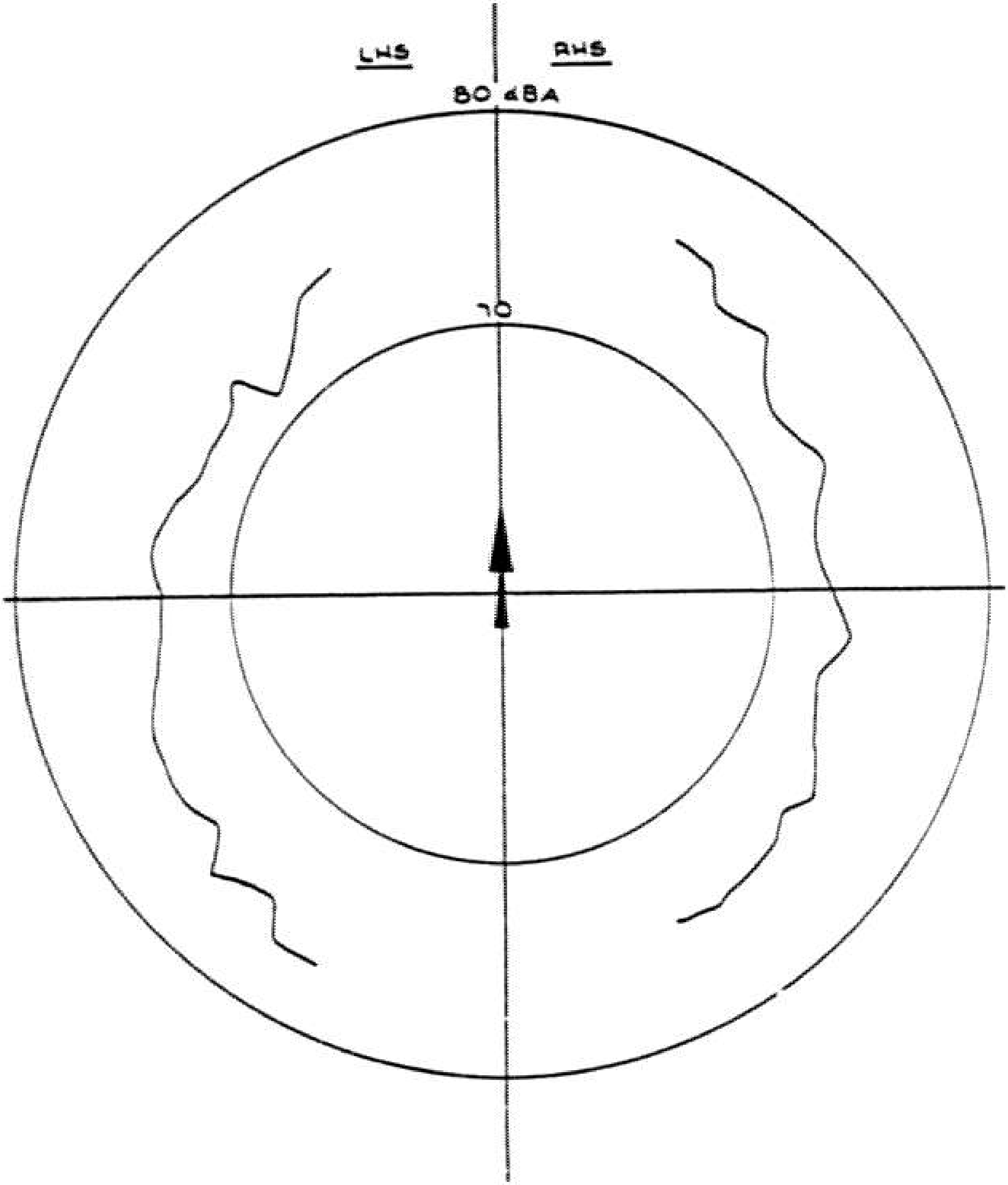


FIGURE 3-73. POLAR PLOT OF NOISE DISTRIBUTION CHRYSLER ALPINE 'S', 30 MILE/H, 2ND GEAR

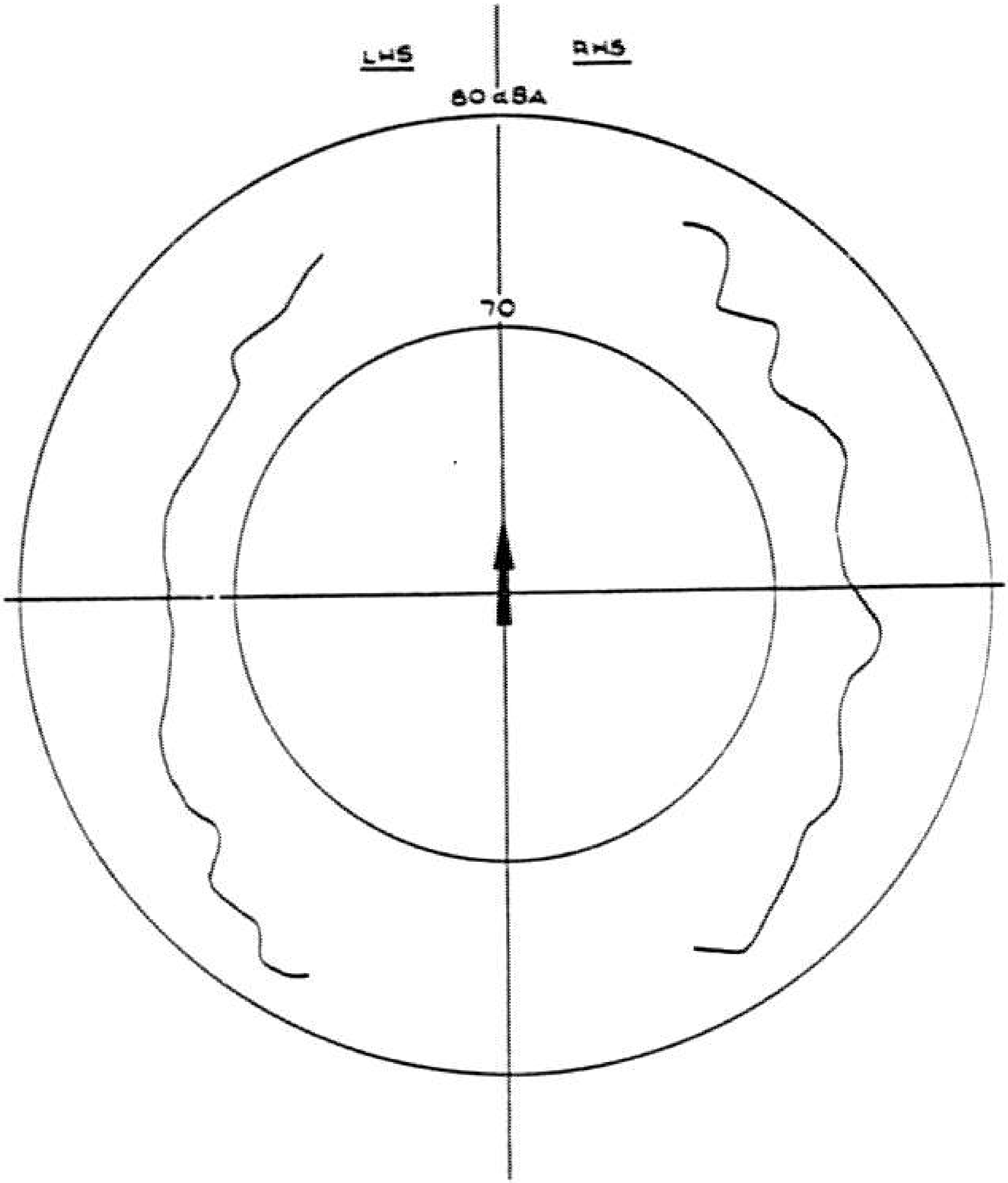


FIGURE 3-74. POLAR PLOT OF NOISE DISTRIBUTION
VOLVO 244GL, 30 MILE/H, 2ND GEAR

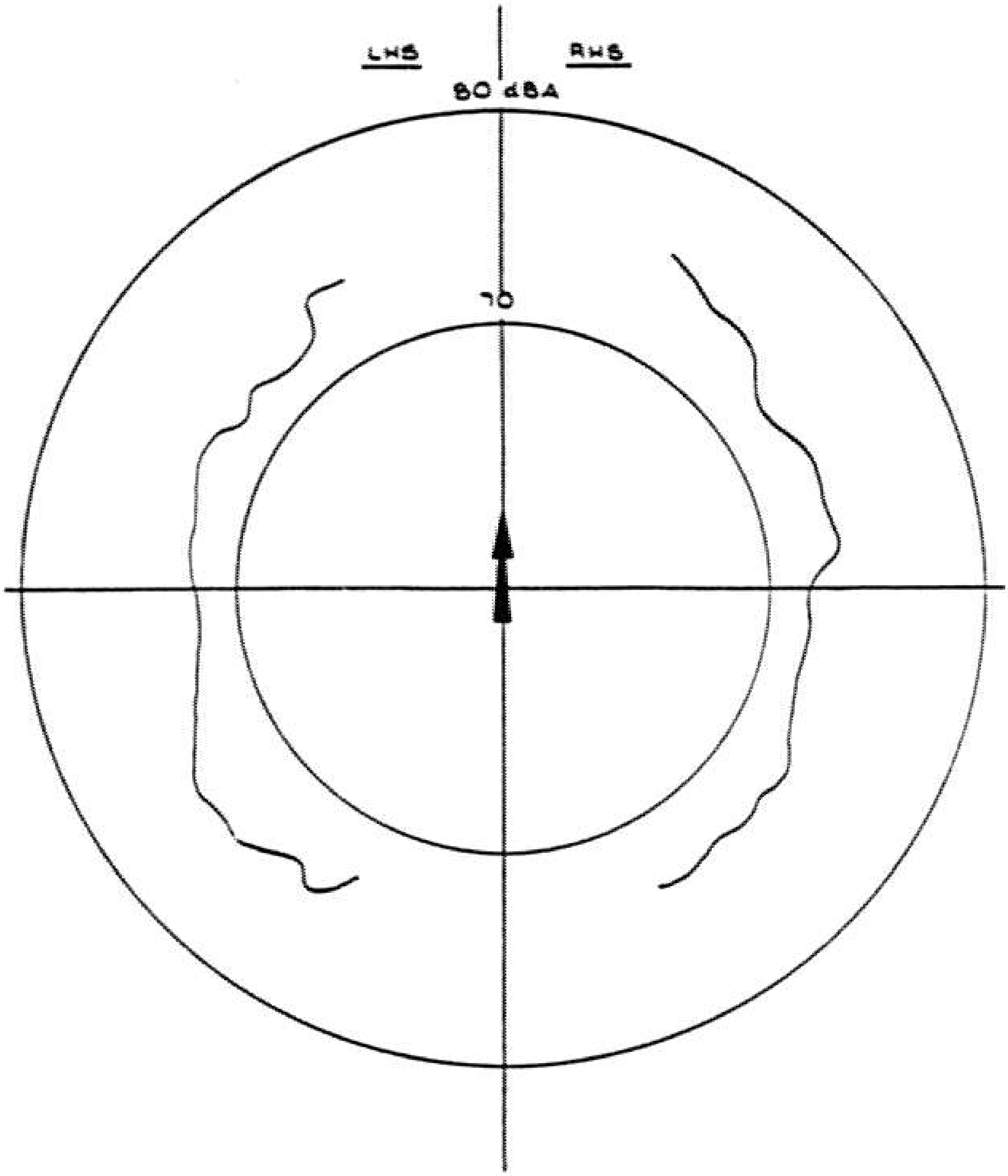


FIGURE 3-75. POLAR PLOT OF NOISE DISTRIBUTION
SAAB 99GL INJECTION, 30 MILE/H,
2ND GEAR

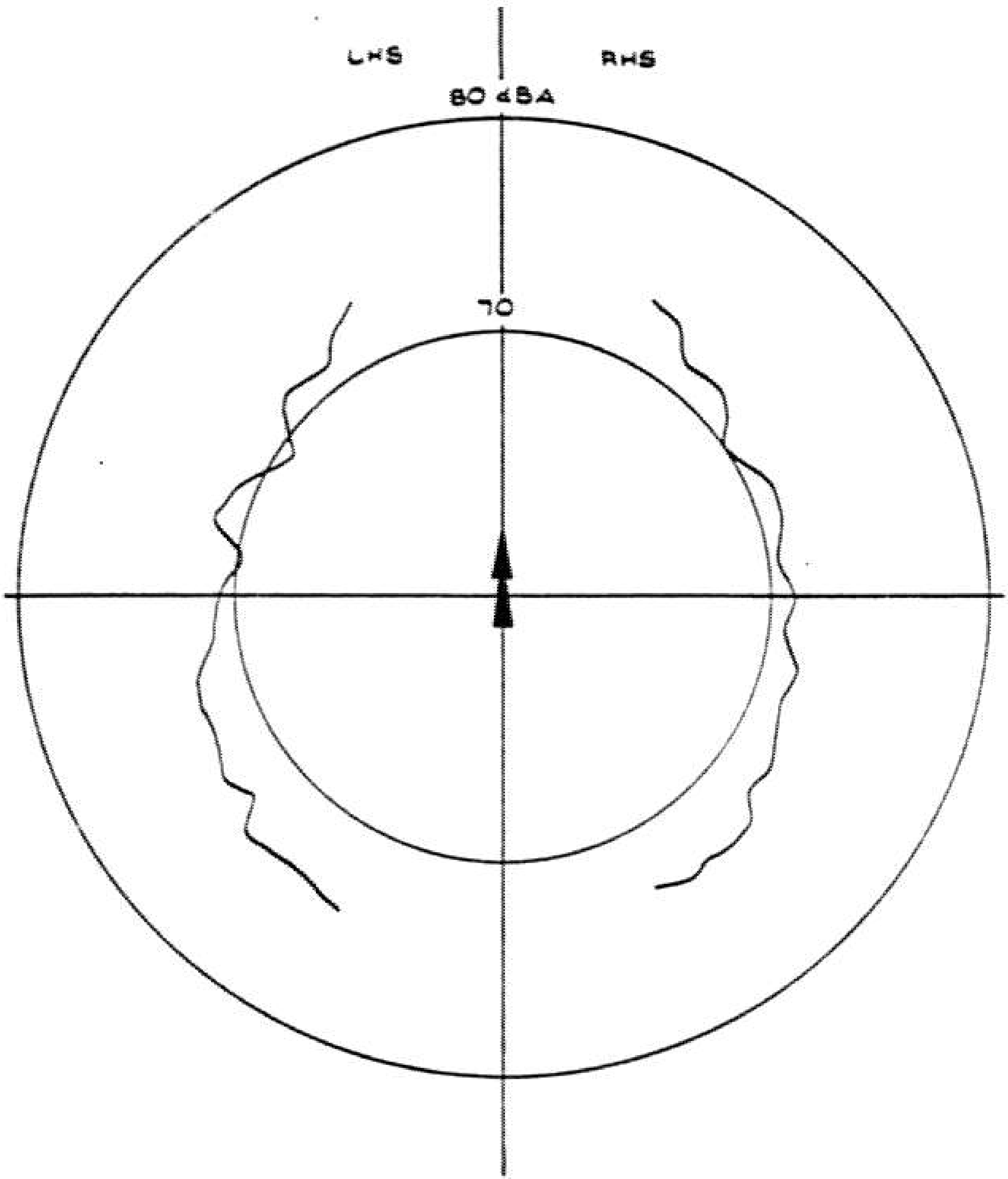


FIGURE 3-76. POLAR PLOT OF NOISE DISTRIBUTION
JAGUAR XJ6 4-2, 30 MILE/H, "D2"
GEAR

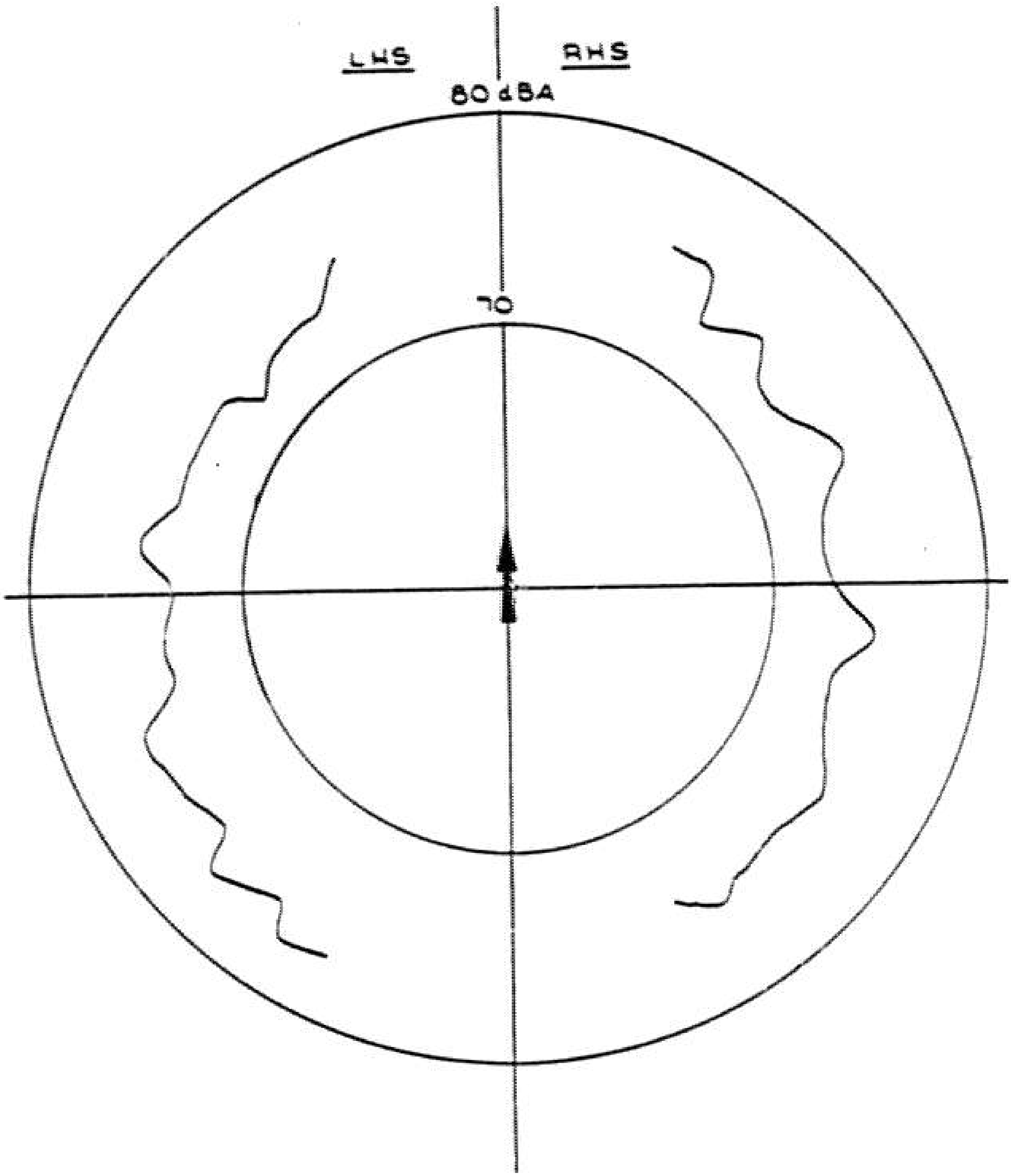


FIGURE 3-77. POLAR PLOT OF NOISE DISTRIBUTION
TRIUMPH DOLOMITE SPRINT, 30 MILE/H,
2ND GEAR

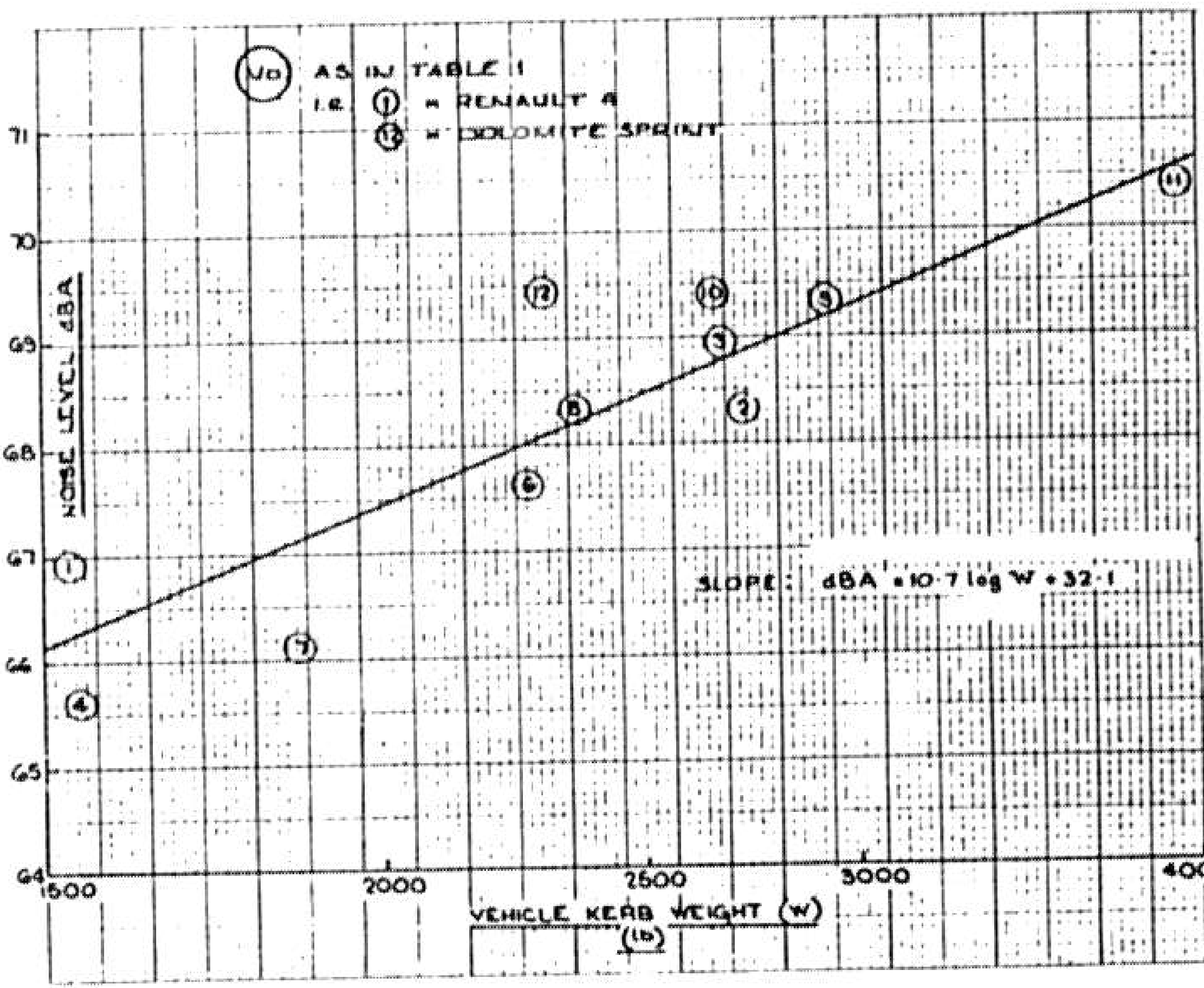


FIGURE 3-78. COAST-BY NOISE V CURB WEIGHT - NOISE LEVEL IS MAXIMUM MEASURED AT MIC. 2 POSITION, 30 MILE/H

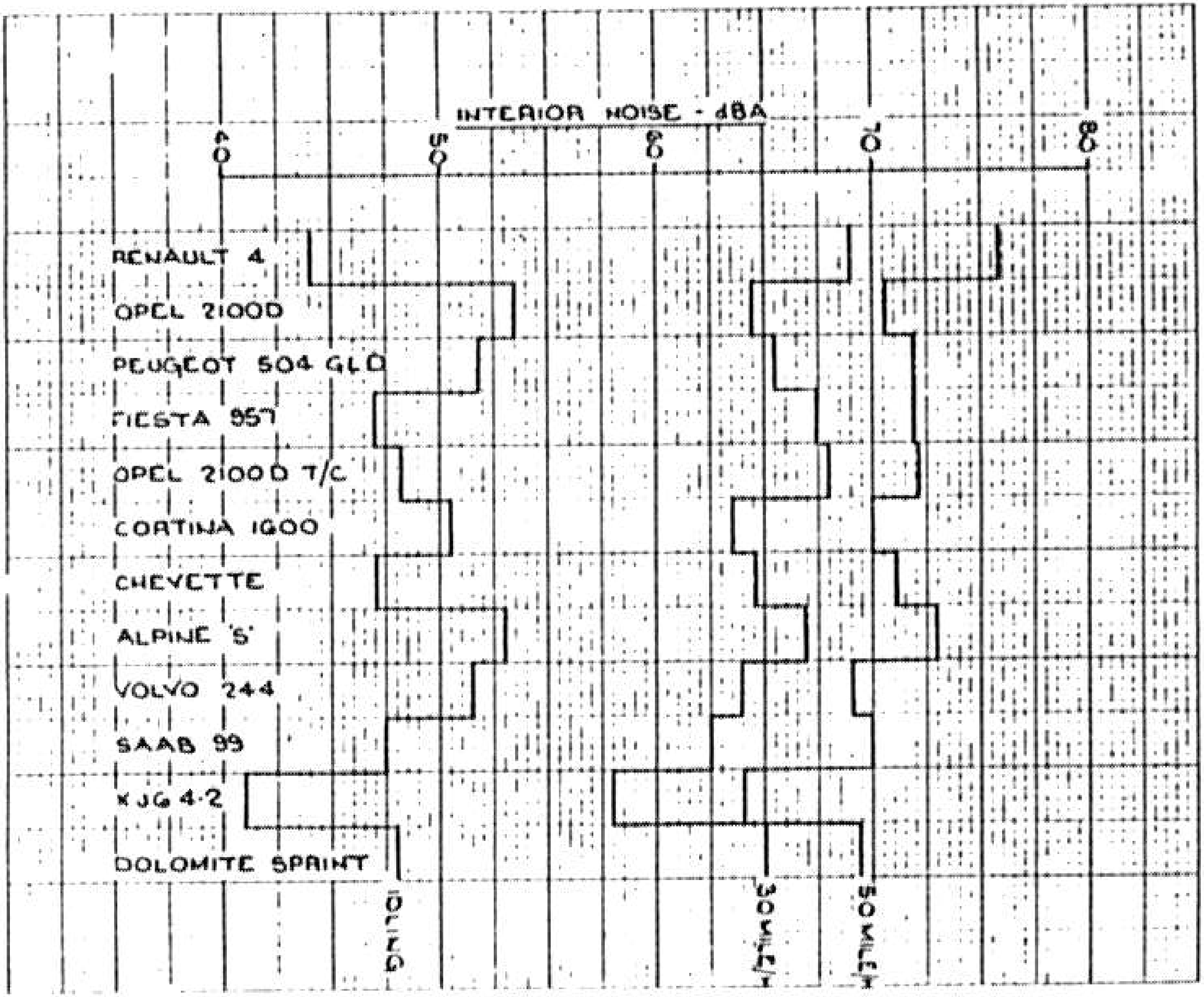


FIGURE 3-79. INTERIOR NOISE MEASUREMENTS AT IDLE, 30 AND 50 MILE/H

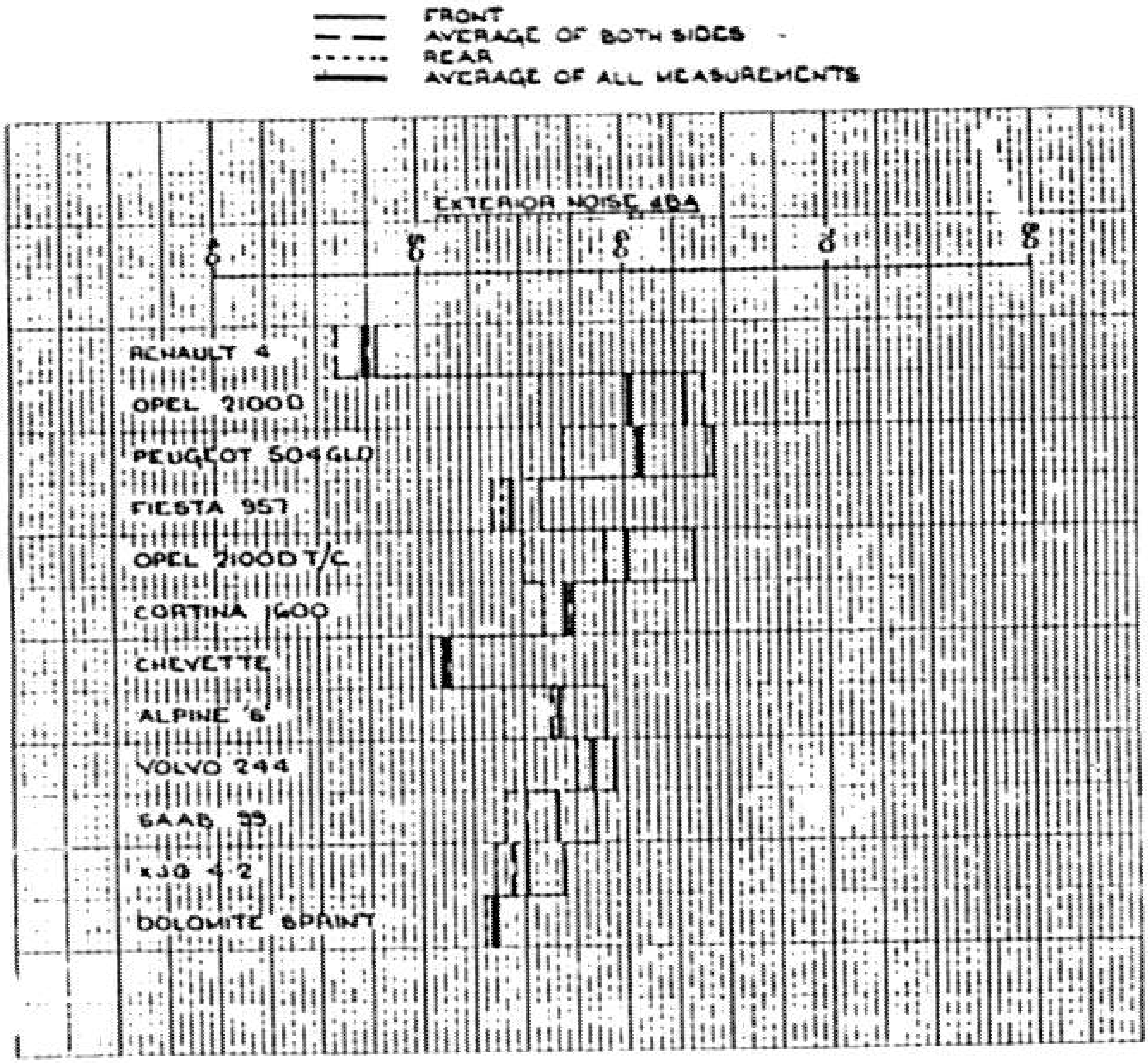


FIGURE 3-80. EXTERIOR NOISE MEASUREMENTS WITH ENGINE IDLING AND VEHICLE STATIONARY - MEASURED 3m FROM VEHICLE BODY MEASUREMENT POSITION

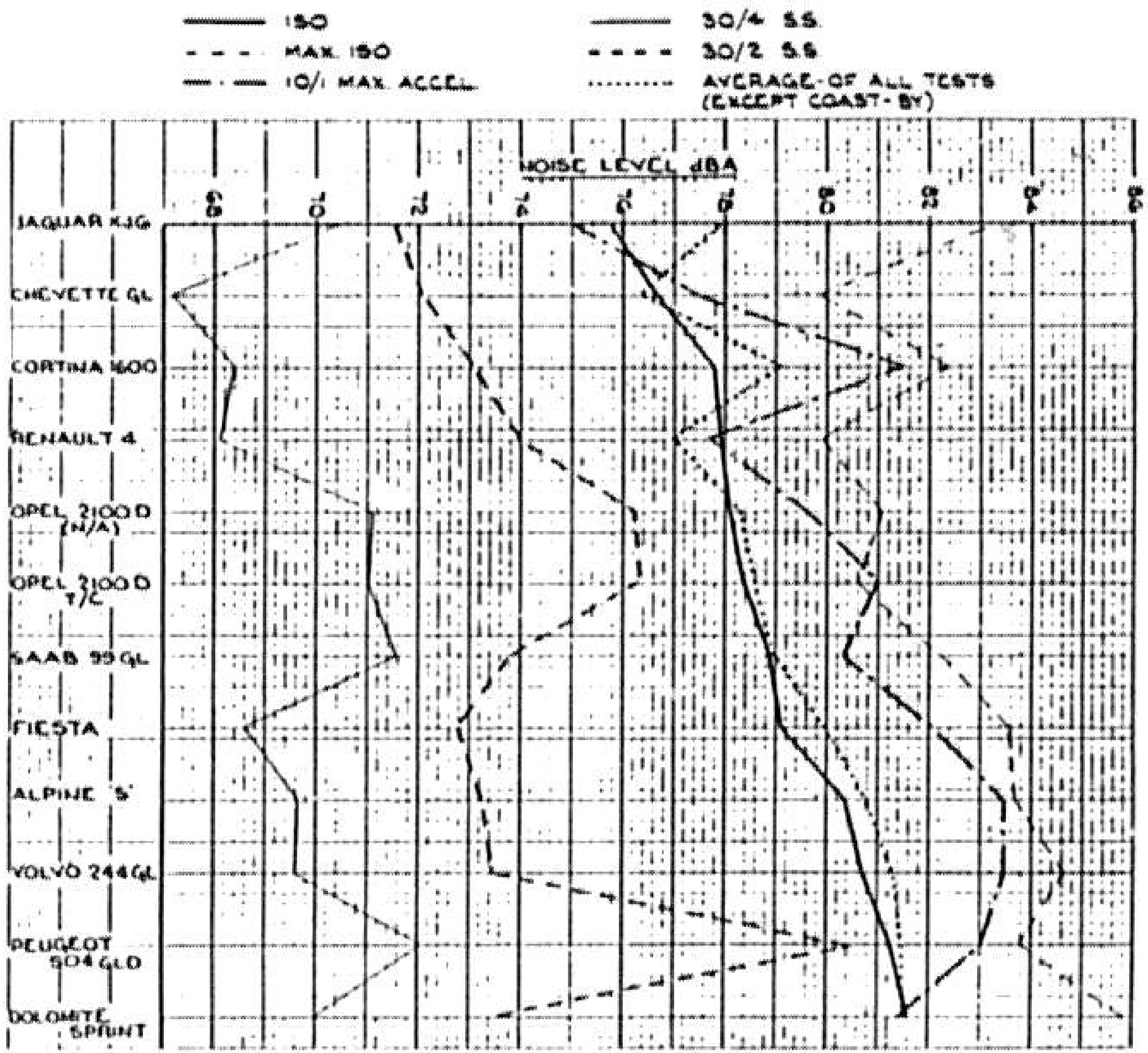


FIGURE 3-81. DRIVE-BY NOISE LEVELS AT MIC. 2 POSITION AVERAGE OF LHS AND RHS RUNS

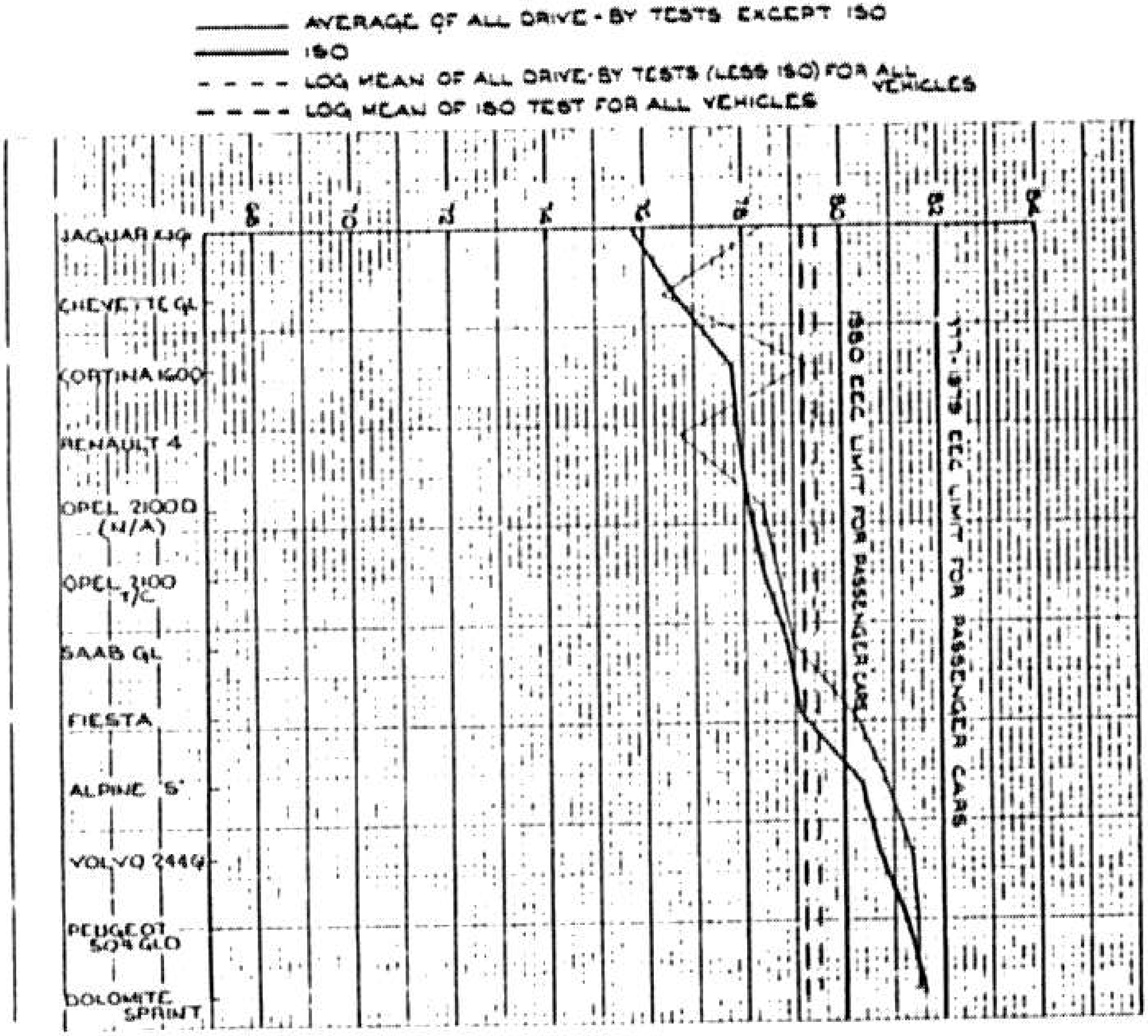
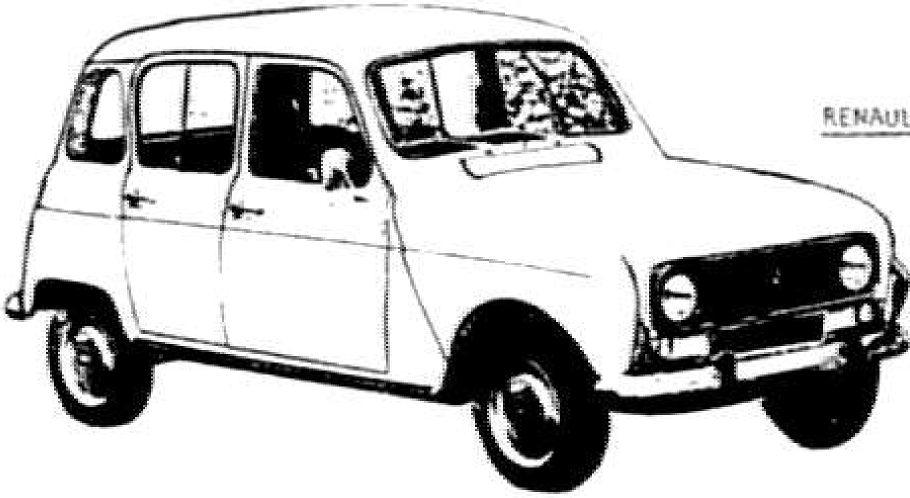


FIGURE 3-82. COMPARISON OF VARIOUS DRIVE-BY TESTS WITH STANDARD ISO

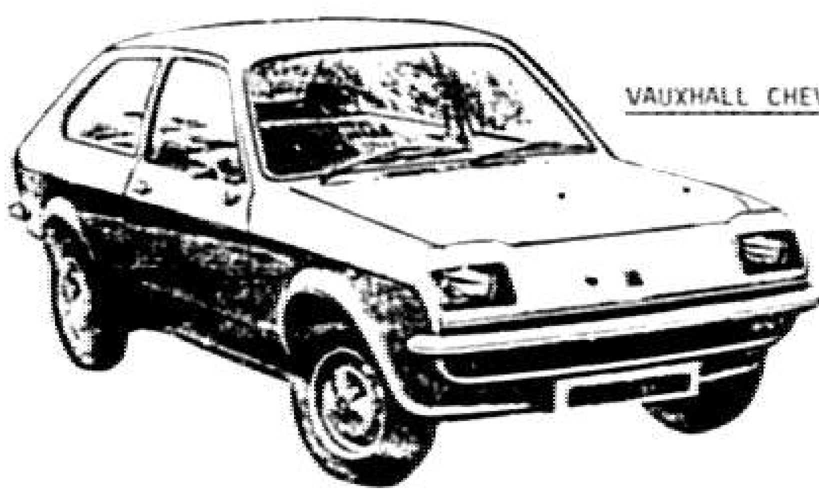
APPENDIX I.

ILLUSTRATIONS OF VEHICLES TESTED

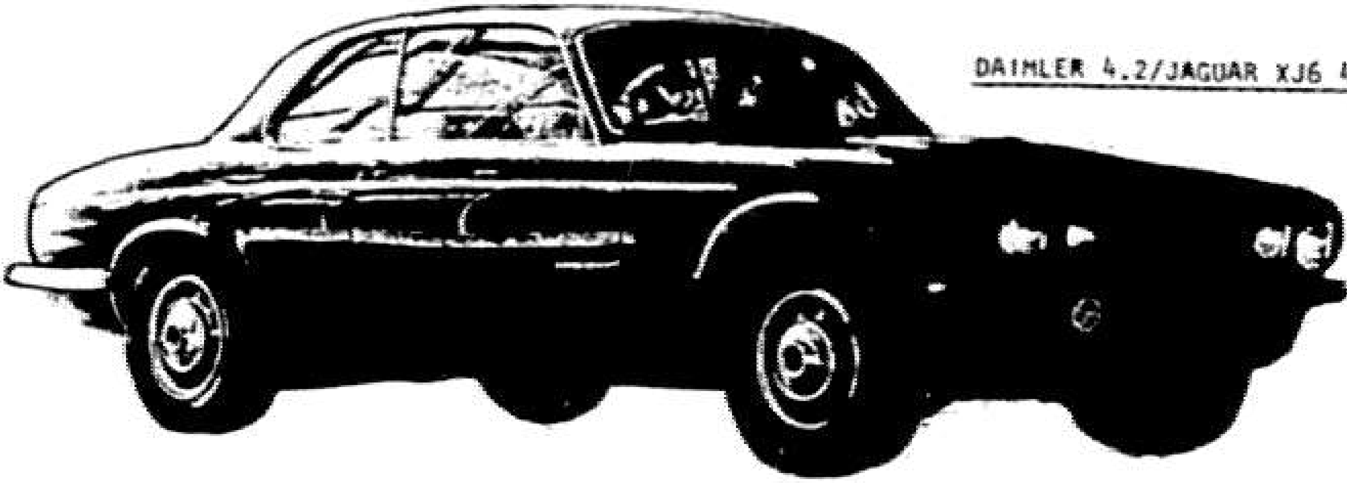


RENAULT 4

FORD FIESTA



VAUXHALL CHEVETTE GL



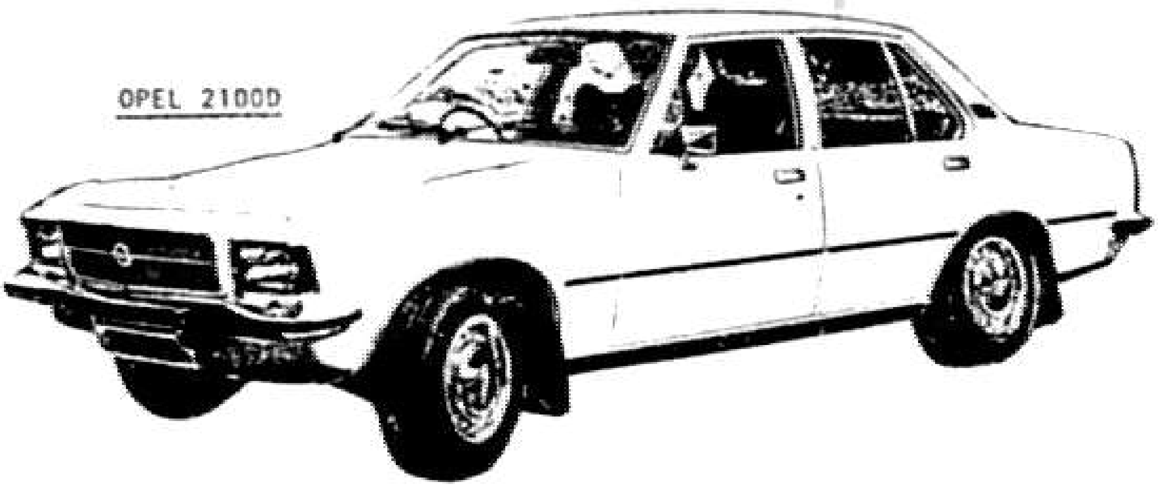
DAIMLER 4.2/JAGUAR XJ6 4.2

TRIUMPH DOLOMITE SPRINT

CHRYSLER ALPINE S

VOLVO 244 GL

OPEL 2100D



FORD CORTINA 1600

4. TESTS ON A SAAB B.I. 2-LITRE GASOLINE ENGINE

4.1 INTRODUCTION

This report describes the test work carried out in an anechoic chamber on a SAAB B.1. 2-litre spark ignited gasoline engine (90 x 78 x 4 cyl) as part of an overall program of noise, performance, economy and emissions evaluation on two passenger cars and their respective engines. The cars were a Peugeot 504 GLD (diesel engine) and a SAAB 99GL Injection. The test work on the vehicles was initially reported in Ricardo report DP 77/1158.

Report DP 79/821 covers the tests on the Peugeot XD2 engine (as fitted to the Peugeot 504 GLD car). Report DP 79/685 covers the work on the ten additional European passenger cars. The overall objective of the program was to assess the noise, performance, economy and exhaust emission characteristics of the type of engine commonly used in Europe, designated a "high speed engine", in two forms: diesel and gasoline. The SAAB 99GL and Peugeot 504 GLD were chosen as broadly representative of typical European cars and were procurred in 1976 California emission build. The engines were retained in their low emission build for the anechoic chamber noise tests.

4.2 TEST ENGINE

The engine tested was a SAAB B.1. 1.985-litre spark ignited gasoline engine in standard 1976 California emission build and complete with manual transmission. A full description of the engine is given in Table 4-1. The transmission was specially modified by Ricardo to permit power to be taken from the pinion shaft, at engine speed. This was preferred to locking the differential unit and driving the dynamometer from one of the normal drive shafts. A sketch of the modifications made is shown in Figure 4-1. The engine was as fitted in the SAAB 99GL car, which was the subject of detailed drive-by tests as referred to above.

4.3 TEST FACILITY

The engine was installed in Ricardo Anechoic engine test cell 'D', with the exhaust and intake piped outside the cell through Burgess ADS 6 silencers. The cell dimensions were 5m x 4m x 4m and the inner surfaces were covered in 100mm Dunlop DF 119 polyurethane foam. Engine power was absorbed by a Schenck 130 dynamometer installed in an adjoining control room and driven by the engine through a plummer block mounted coupling shaft.

The arrangement of the microphones around the engine is shown in Figure 4-2. Four microphones were used, each one one meter from the engine surface. The microphones are designated Mic. 1 (Right Hand Side), Mic. 2 (Left Hand Side), Mic. 3 (Front) and Mic. 4 (Overhead). For one series of tests an 8 microphone array was used for a sound power level calculation. This is described more fully in Section 4.4.2 and 4.6.2.

The standard noise measuring and monitoring instrumentation is listed in Table 4-2.

4.4 TEST PROCEDURE

A detailed speed/load test matrix was followed for the majority of the tests, covering a wide range of typical engine operating conditions covering speeds from 20 to 90 rev/s (in 10 rev/s increments) and loads from 0 to 100 percent (wide open throttle) in bmep increments of 1 bar over the light load, low speed conditions and increments of 2 bar over the remainder of the matrix.

4.4.1 Performance and Fuel Consumption

At conditions of wide open throttle (WOT), brake torque and fuel consumption were measured over the speed range. The fuel consumption was also measured at a number of part-load conditions.

4.4.2 Basic Noise Measurements

The sound pressure level was measured at each of the four microphone positions shown in Figure 4-2 over the engine speed and load range including idle. Both linear and A-weighted levels were recorded together with 1/3rd octave frequency spectra for each point. At selected points, cylinder pressure spectra were obtained. For all tests the exhaust and intake noise sources were attenuated by means of the normal test cell silencers located on the roof. All noise level data were tape recorded on a 7 channel FM tape recorder.

The first series of tests were conducted at standard ignition timing (12° BTDC @ 13 rev/s with vacuum pipe disconnected). In order to provide data to enable the calculation of the mechanical/combustion source contributions, selected conditions were repeated for ignition timings of 19°E and 22°E. Retarded timings were not evaluated because of the even further reduced contribution of the combustion noise, the prime object of these tests being to establish the combustion/mechanical noise sources. The procedure used for calculating the combustion/mechanical breakdown was that described in Ricardo report DP 76/832.

A series of sound power level measurements were made using a standard 8 microphone array. The array used in shown in Figure 4-3.

4.4.3 Exhaust Emissions

Exhaust emission measurements were made over the speed/load range at selected points. NO, CO and HC levels were measured using the Cussons Ricardo P7500 Comprehensive Analytical Unit with NDIR analysers for CO, CO_2 and NO plus FID analyser for HC.

4.5 TEST RESULTS

4.5.1 Performance and Fuel Consumption

The wide open throttle performance curves are shown in Figure 4-4. The results shown are corrected using the DIN 70020 correction formula and standard ambient conditions of 20°C and 760mmHg barometric pressure. The effect of timing on performance is shown in Figure 4-5.

The effect of load and speed on specific fuel consumption is shown in Figure 4-6.

4.5.2 Basic Noise Measurements

Unless otherwise stated, all sound pressure levels are to a reference pressure of 20μPa.

The effect of speed and load on the overall sound pressure level at each of the four microphone positions is shown in Figures 4-7 - 4-10. Sound pressure level spectra corresponding to a selection of representative points are given in Figures 4-11-4-20. The effect of speed (for 100 percent load conditions) is shown in Figures 4-11-4-14 and the effect of load for various speed conditions (30, 50, 90 rev/s) is shown in Figures 4-15-4-17. The effect of ignition timing changes on the overall sound pressure level and the spectrum shape is shown in Figures 4-18-4-20 for various speed/load conditions.

Idle noise frequency spectra for the hot idle conditions are shown in Figure 4-21 for all 4 microphone positions.

Cylinder pressure spectra for various speed/load combinations for the standard engine are shown in Figures 4-22-4-29. Figures 4-22-4-25 illustrate the effect of speed at 100 percent load. Figure 4-26 shows the effect of load at 20 rev/s, and Figures 4-27-4-29 the effect of advancing the ignition timing at 30, 50 and 90 rev/s. From these latter tests, the combustion/mechanical breakdown was calculated and the results are shown plotted for the 100 percent load conditions for the right and left sides on Figures 4-30 and 4-31.

The results of the 8 microphone array sound power tests are given in Table 4-3.

4.5.3 Exhaust Emissions

The NO, HC and CO exhaust emission levels expressed in ppm are shown in Figures 4-32-4-34. These three dimensional plots indicate the emission trends over the speed and load range.

4.6 DISCUSSION AND COMMENTS

4.6.1 Performance and Fuel Consumption

The measured full load performance agrees closely with the figures stated by SAAB. At 90 rev/s Ricardo measured 71.5kW (SAAB 73kW). The peak bmep was 9.4 bar, the same as specified by SAAB. The maximum power figure for this California build engine is some 20 percent less than that of the European engine fitted with fuel injection, as a result of the emission control modifications (primarily exhaust gas recirculation, manifold air oxidation, reduced compression ratio, single branch exhaust manifold and retarded ignition timing). The measured specific fuel consumption at wide open throttle displays a "hump" in the mid speed range, this corresponding with the rise in torque over the same range. This somewhat unusual curve shape is probably due to the characteristics of the fuel injection tailoring for emission control.

The part load fuel consumptions shown in Figure 4-6 show the expected "loop" shape over the load range for a given engine speed, the high consumption at part load arising from the reduced efficiency as a result of throttling and the high consumption at full load being due to frictional and breathing losses.

The effect of ignition timing on full load performance, as shown in Figure 4-5, indicates generally an improvement in bmep (up to 6 percent) by advancing the timing 7° crank from standard (from 12°E to 19°E). This advanced timing corresponds more closely to that of the European build engine (17°E). Further advancing to 22°E slightly worsened the performance (from standard) this being an over-advanced condition which was necessary for the combustion/mechanical noise breakdown.

4.6.2 Noise

The noise level measured at rated speed (90 rev/s) and full load was 99.5 dBA at one meter (average of the 4 microphone positions). This agrees very closely with the Ricardo prediction formula for automotive gasoline engines which gives a level of 99 dBA (± 2 dBA) at the same conditions. There was very little deviation from this average level around the engine, the highest being at the left hand side (100.5 dBA) and the lowest at the front (98.8 dBA).

The effect of engine speed on noise levels at full load is characteristic of "high-speed" light duty engines, displaying a marked discontinuity in the plot of noise against speed in the mid speed region (60 rev/s). This is particularly clearly seen for the right hand side noise levels (Figure 4-7). Over the speed range 30-60 rev/s the full load noise increases with speed at the rate of 25 dBA/decade. From 60 rev/s to rated speed the slope increases significantly to 70 dBA/decade. For a gasoline engine where the combustion excitation controls the overall radiated noise and where the forcing function remains practically constant, a slope more of the order 50 dBA/decade might be expected. This 50 dBA/decade is only an approximate guideline in indicating possible piston slap effects. The two-slope characteristics of the SAAB noise/speed curve is particularly interesting from two aspects. First, the slope difference is very clearly displayed. It is generally thought that this slope change is due to the changing balance between inertia and gas loading on the piston, such that at low speeds, piston slap prevails, as a result of the gas load overcoming the low inertia load. At high speeds, however, the inertia load may be counteracting the net force on the piston, thus reducing one of the main factors influencing piston slap. Second, the very high rate of increase of noise with speed of the 60-95 rev/s range suggests a "smooth" forcing function (i.e., low rate of increase of force or pressure); the SAAB 99 engine is generally noted for its subjective "smoothness" particularly at high speed.

The response of noise level to load is typical for a gasoline engine, being approximately 8 dBA (from no load to full load) at 20 rev/s, to 2-3 dBA at 90 rev/s. The difference across the speed range is probably due to the greater relative influence of gas load on piston slap at low speeds (as discussed above).

The idle noise is typically low for a gasoline engine, being 63-64 dBA at 1m. Not only is the measured noise low but the engine at idle also sounds subjectively acceptable due to the relatively flat sound pressure level frequency spectra (Figure 4-21).

The sound pressure level frequency spectra display typical features for an engine of this type. The high levels at the firing frequency are normal and of little significance when A-weighted to approximate to the human ear response. As with most engines, the acoustic energy, as far as this affects the perceived noise, is concentrated in the mid to high frequencies (roughly 400 Hz to 5 kHz). The shape of this important part of the spectrum is usually dictated by such factors as free-free beam bending of the crankcase (for an engine of this size, this usually occuring around 500-700 Hz), crankcase panel vibration (usually around 2 kHz), light pressed steel covers (around 800 Hz to 2 kHz) and by certain bolted-on components (e.g., manifolds). It is not within the scope of this study to identify detailed aspects of the spectrum but essentially to establish that the noise signature is typical for the class of engine and generally indicate the significance of the various parts of the spectrum.

The cylinder pressure spectra display the expected steep rate of decay for a gasoline engine (i.e., around 50 dB/decade) with no sudden discontinuties indicating a rapid rate of pressure rise (and therefore, a combustion harshness). In some cases rates of decay as great as 60 dB/decade were seen (at 70 rev/s, full load) suggesting low rates of pressure rise and "smooth" combustion. The effect of load on the cylinder pressure spectrum, as evident from Figure 4-26, (i.e., of the order 10-15 dB) is considerably greater than that of load on the radiated noise. This therefore suggests an insignificant combustion noise effect, as the large change in combustion noise has not been reflected on the change in radiated noise over the same load range. This conclusion is supported by the combustion/mechanical breakdown results where it is shown (Figures 4-30 and 4-31) that at standard ignition timings, mechanical noise controls the overall noise level at full load over the speed range 30-70 rev/s (the effect of speeds outside this range was not evaluated). This domination of the mechanical noise in high speed engines (and in particular, gasoline engines where the combustion excitation is usually minimal as far as noise is concerned) is typical. Mechanical noise as defined by Ricardo in this context is a combination of such factors as piston slap, rotating components (crankshaft, camshaft), valve train, auxiliaries and crankcase panel vibration.

The sound power level was calculated from the standard microphone array results by first calculating the sound intensity at each microphone position, this value being corrected for the intensity at the surface of a 1m radius sphere. In this particular case the sphere was centered in the middle of the cylinder head gasket left-hand edge. The intensity at each microphone position was then assumed to be representative of the intensity over a part of the sphere's surface, the area of this surface being determined from the ratios of the areas projected by the corresponding aspects of the engine. Thus the areas 'sampled' by Mics. 1 and 2 are larger than that of Mic. 3 (for example). The sound power represented by each of the 4 'sampled' areas on the sphere's surface was then calculated and summed, and the total sound power being emitted through the sphere was calculated by assuming that the average intensity over the 4 sampled areas was the same as the average for the whole sphere. In this case, the 'sampled' areas accounted for 70 percent of the total sphere surface, thus this assumption seems valid. The results (A) are shown below.

The sound power level was also calculated from the 8 microphone array by averaging each sound pressure level, correcting to a 1m radius and adding 11 dB.

Correlation between results obtained using the 8 Mic. array and the standard 4 Mic. array was good, the difference in the value of the sound power level of the engine as calculated by the two different methods varying from 1.2 dB at 20 rev/s to 0.3 dB at 50 rev/s, as shown in the table below.

Finally, if the standard 4 Mic. array results are taken, simply corrected to a 1m radius, log average and converted to sound power by adding 11 dB, the sound power results are shown in the table below (Results B). It would appear that even this very simple approximation gives very close correlation with the 8 Mic. array results and suggests that sound power can be reliably indicated by only 4 microphones for normal engines.

SOUND POWER LEVEL dBA (REF. 10^{-12} W)

Engine Speed (rev/s)	4 Mic. Array		8 Mic. Array
	(A)	(B)	
20	88.7	88.8	87.5
30	91.8	91.9	91.0
40	95.0	95.1	94.4
50	98.2	98.5	97.9

4.6.3 Exhaust Emissions

The emission characteristics (as assessed by measurements of CO, HC and NO) are generally as would be expected for a light duty gasoline passenger car engine tailored to California 1976 emission specification. The levels of CO, HC and NO levels are all low over the part load, low-mid speed range. The CO levels at full load, ranging from 2-4 percent, are within the optimum range for weakest mixture/minimum power. Over the speed range at low loads, however, the levels drop considerably (i.e., < 0.2 percent) to orders of magnitude typical of what might be expected from a low emission build gasoline engine with manifold air oxidation and at steady-state operating conditions. The same comments apply to the HC results where the levels at part load are also low, especially at high speeds. The NO trends follow the expected inverse of the HC and CO characteristics, with low levels occurring at the relatively rich full load conditions. The levels of NO are typical for an engine of this type set up for 1976 California emission limit of 2 g/mile over the LA4 vehicle test cycle.

TABLE 4-1. ENGINE SPECIFICATION

(FROM MANUFACTURER'S DATA)

Type:	SAAB B.I.
Bore:	90mm
Stroke:	78mm
No. of cyls:	4
Swept Volume:	1.985 litre
Max. brake power:	73kW @ 92 rev/s
Max. torque:	148Nm @ 42 rev/s (9.4 bar bmep)
Idle Ignition Setting:	12° BTDC @ 13 rev/s (vacuum disconnected)
Fuel Injection System:	Bosch K Jetronic continuous injection
Emission Build:	California 1976 with manifold air oxidation, exhaust gas recirculation and single branch exhaust manifold
Compression ratio:	8.7 (for 1976 California build)

TABLE 4-2. STANDARD NOISE INSTRUMENTATION

Microphones:	B & K 12mm capacitor type 4165
Microphone Power Supply:	B & K 2807
Frequency Analyser:	B & K 3347
Cylinder Pressure Transducer:	Kistler 6121
Charge Amplifier:	Kistler 5001
Level Recorder:	B & K 2305

TABLE 4-3. RESULTS OF 8 MICROPHONE ARRAY TESTS

(at engine conditions of full load)

sound pressure levels expressed in dBA

Engine Speed	microphone position (ref. Appendix 3)								
rev/s	1	2	3	4	5	6	7	8	log ave
20	72.6	74.8	69.6	75.6	75.6	76.4	69.8	76.6	74.6
30	77.0	78.4	72.0	79.2	79.6	79.4	70.6	80.6	78.1
40	80.8	81.6	75.6	82.8	82.8	82.4	76.2	83.8	81.5
50	85.8	85.2	77.8	86.2	86.8	85.4	76.6	86.8	85.0

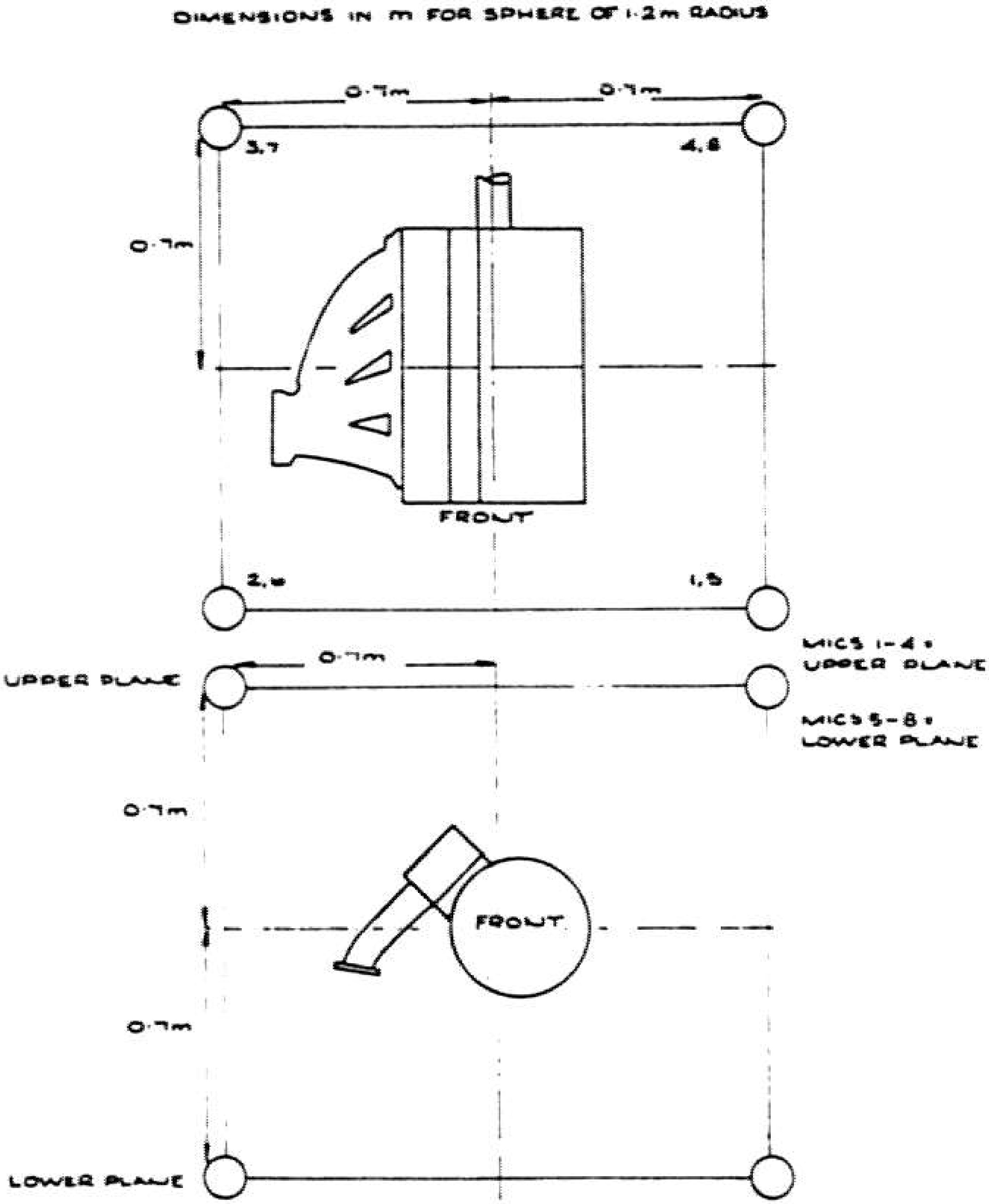


FIGURE 4-1. 8 MIC ARRAY FOR SAAB

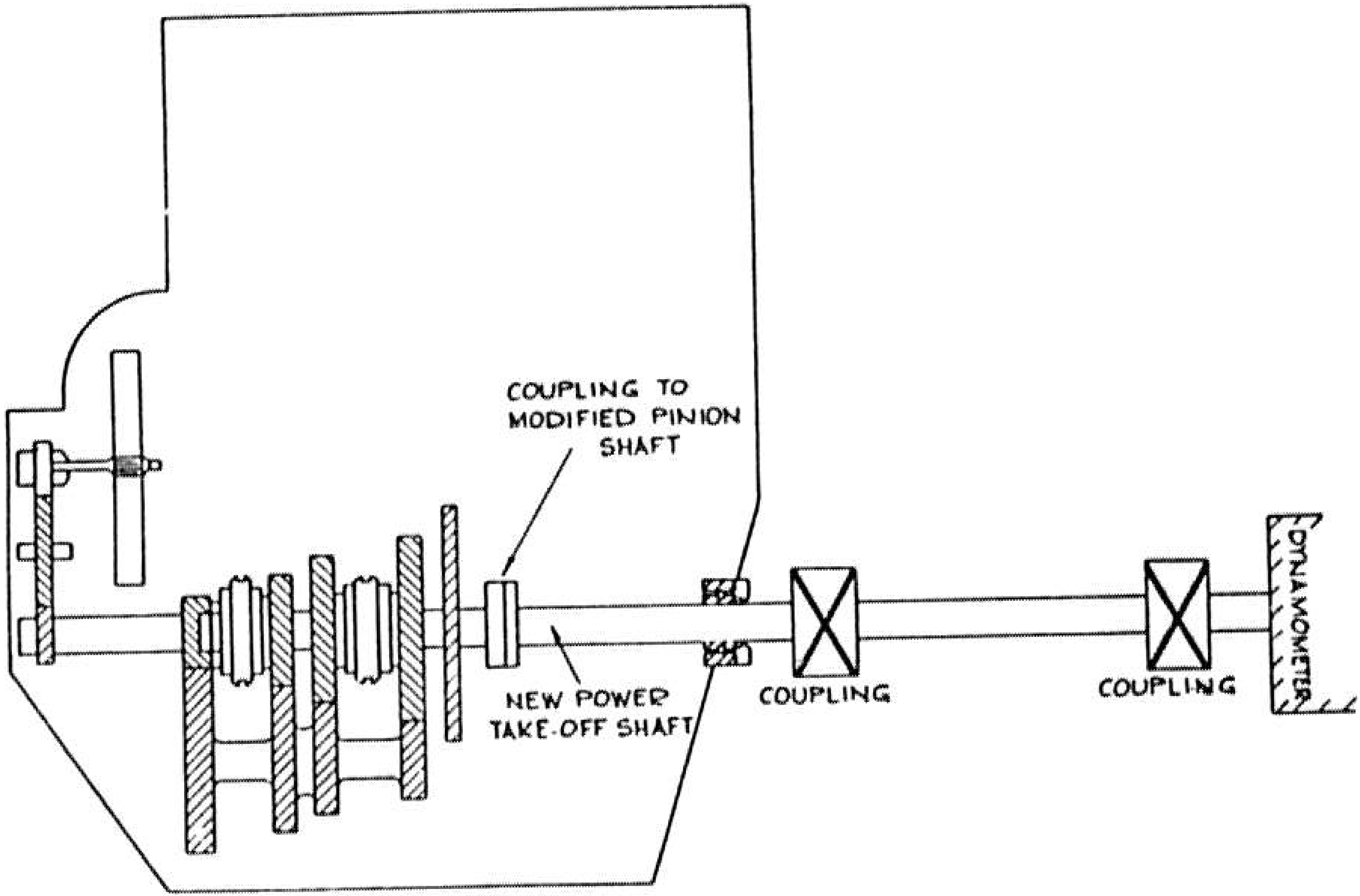


FIGURE 4-2. SCHEMATIC LAYOUT OF TRANSMISSION MODIFICATIONS FOR POWER TAKE-OFF

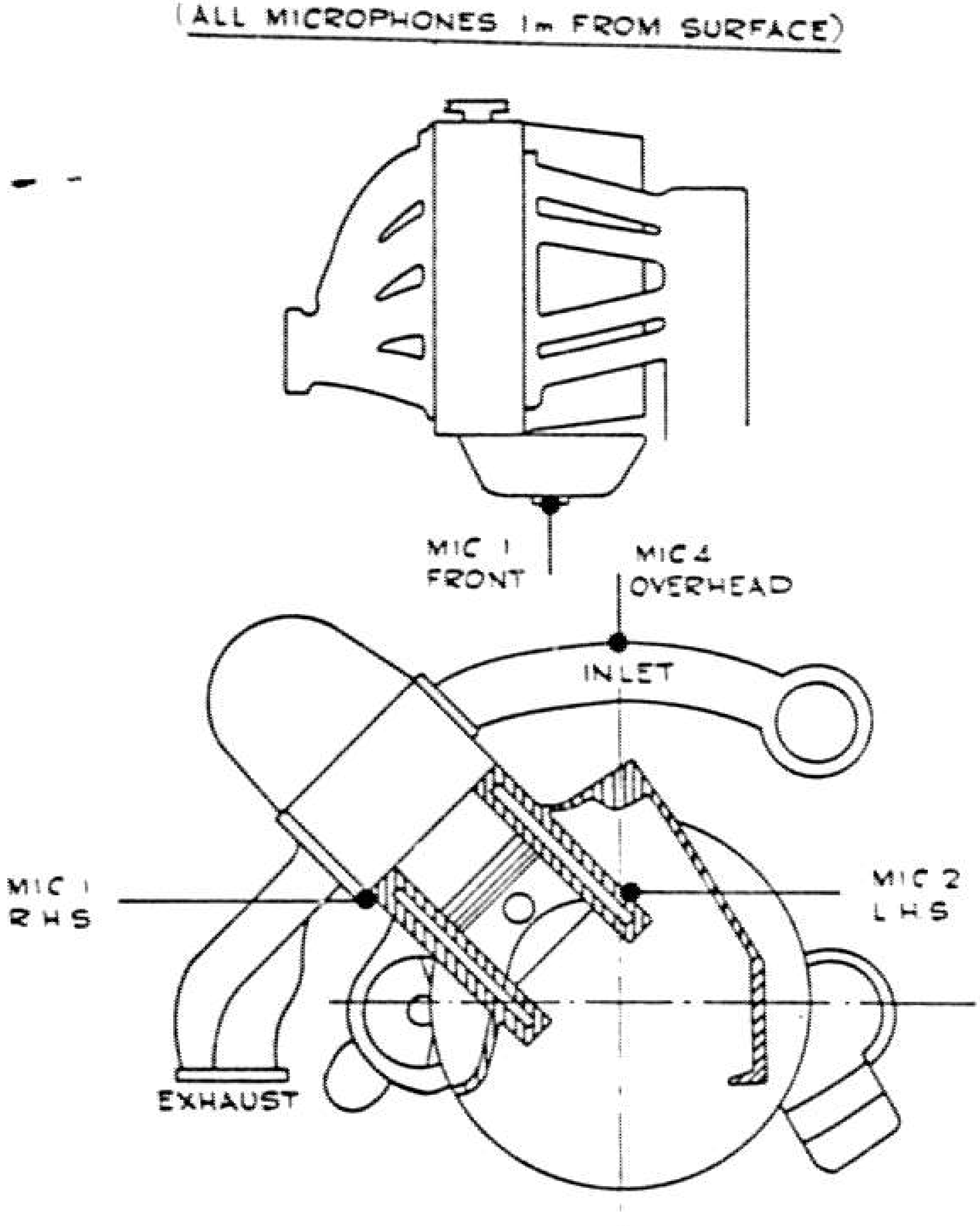


FIGURE 4-3. DETAILS OF 4 MICROPHONE ARRAY (SAAB BI 1 985ℓ 90ϕ x 78 x 4 CYL*)

*All subsequent figures are based upon these engine specifications.

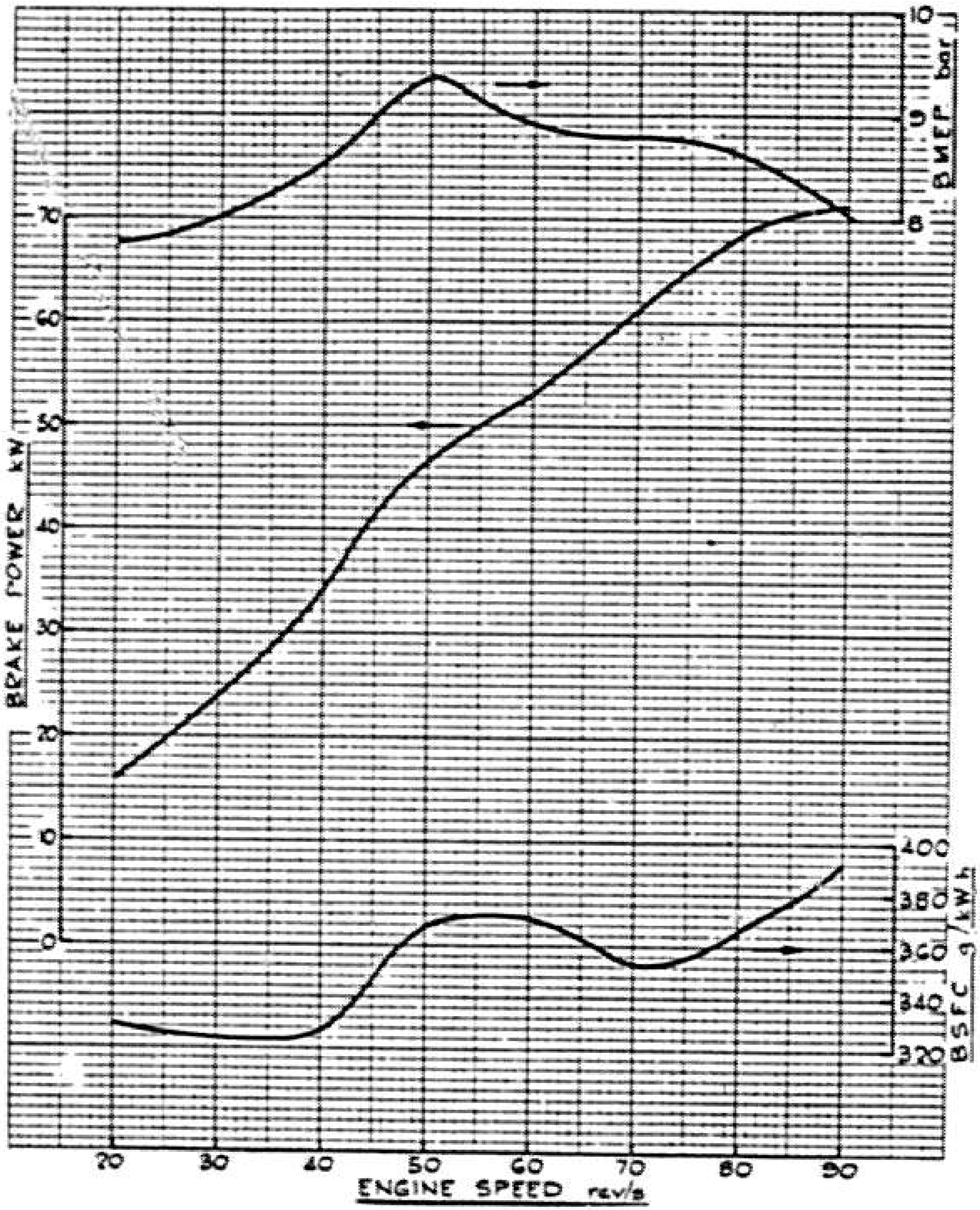


FIGURE 4-4. SAAB BI FULL LOAD PERFORMANCE

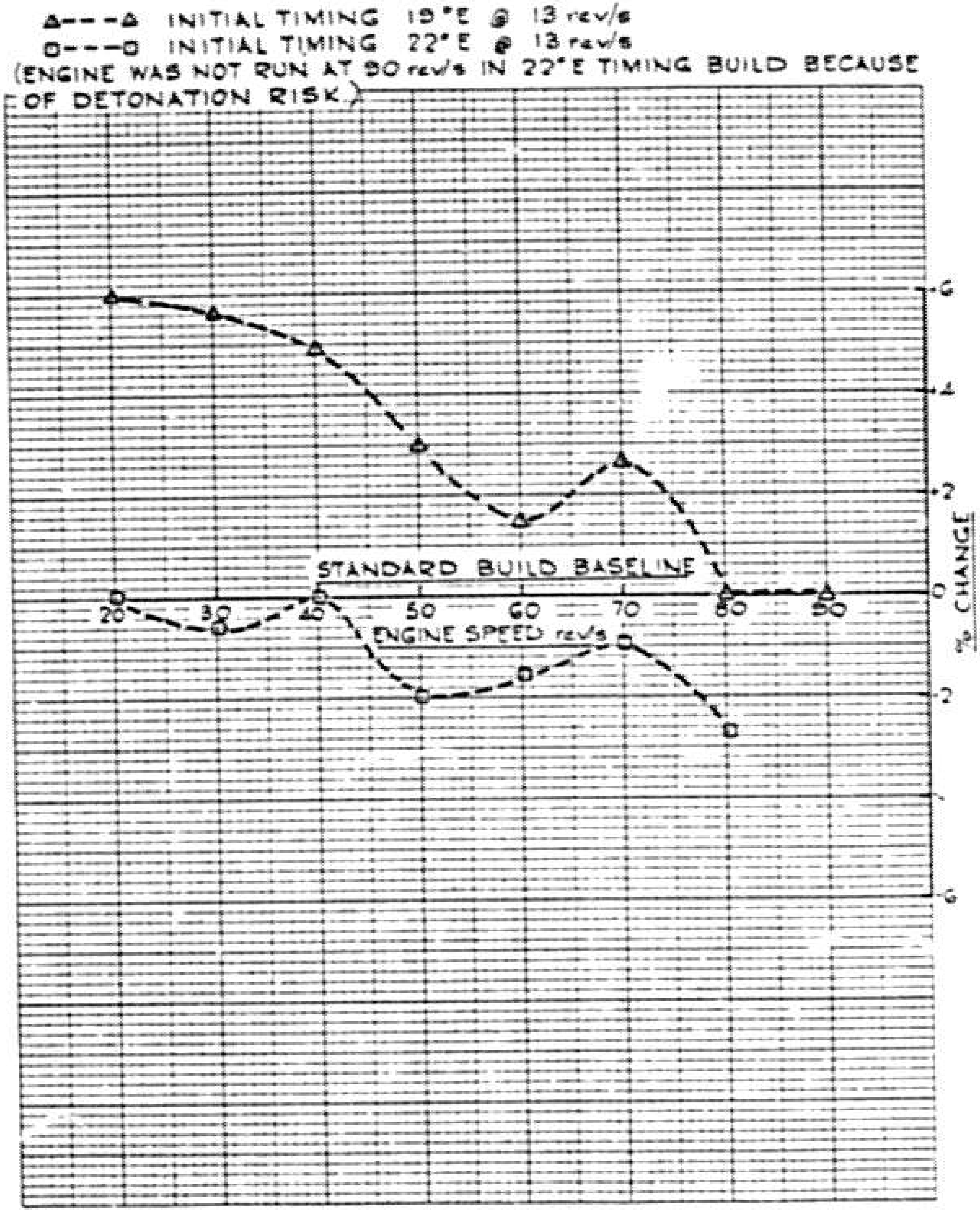


FIGURE 4-5. SAAB BI: PERCENTAGE CHANGE IN B.M.E.P. WITH IGNITION TIMING FROM STANDARD BUILD (12°E)

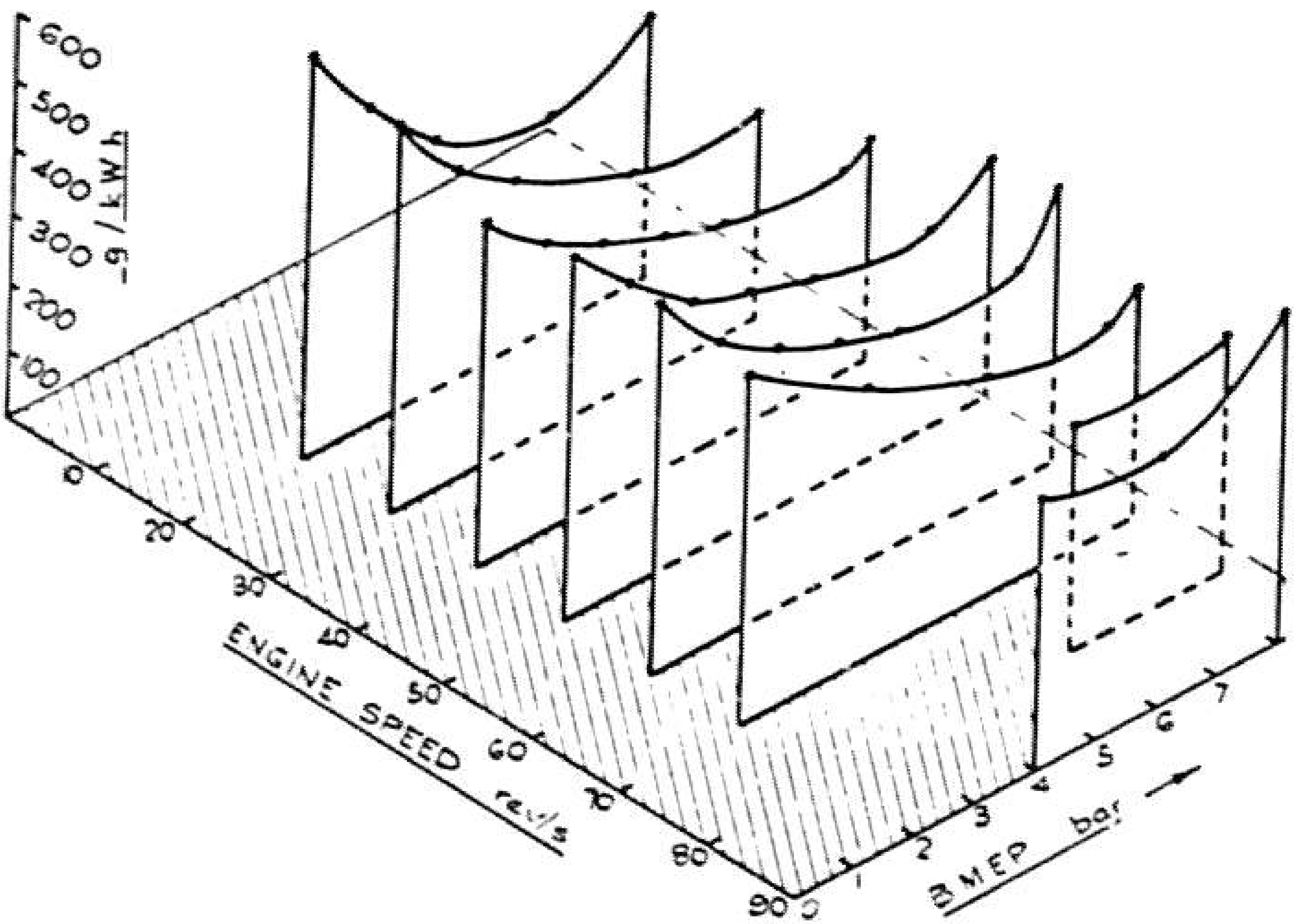


FIGURE 4-6. SPECIFIC FUEL CONSUMPTION OVER LOAD AND SPEED RANGE

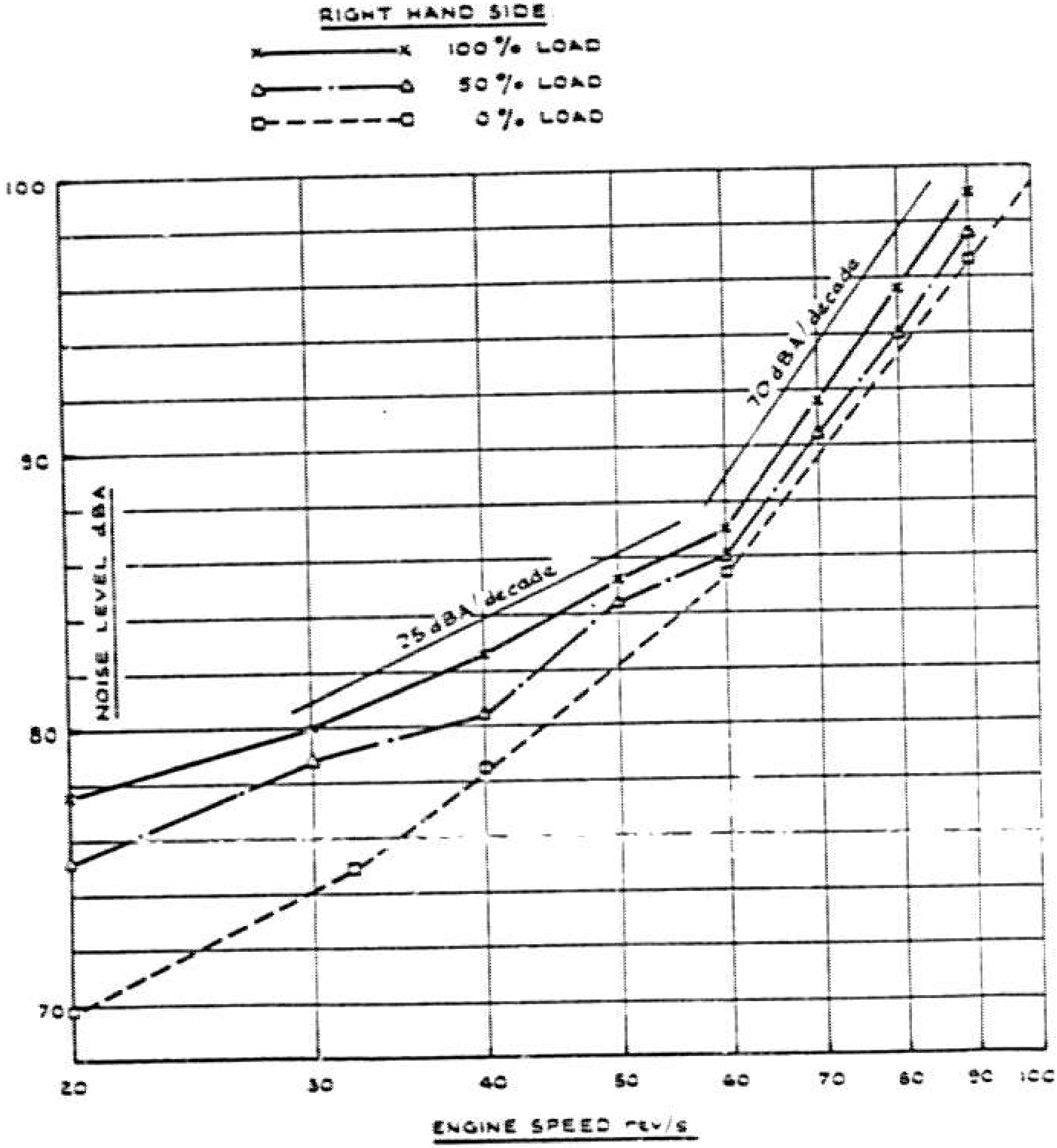


FIGURE 4-7. NOISE LEVELS OVER SPEED RANGE AT 0, 50 AND 100% LOAD

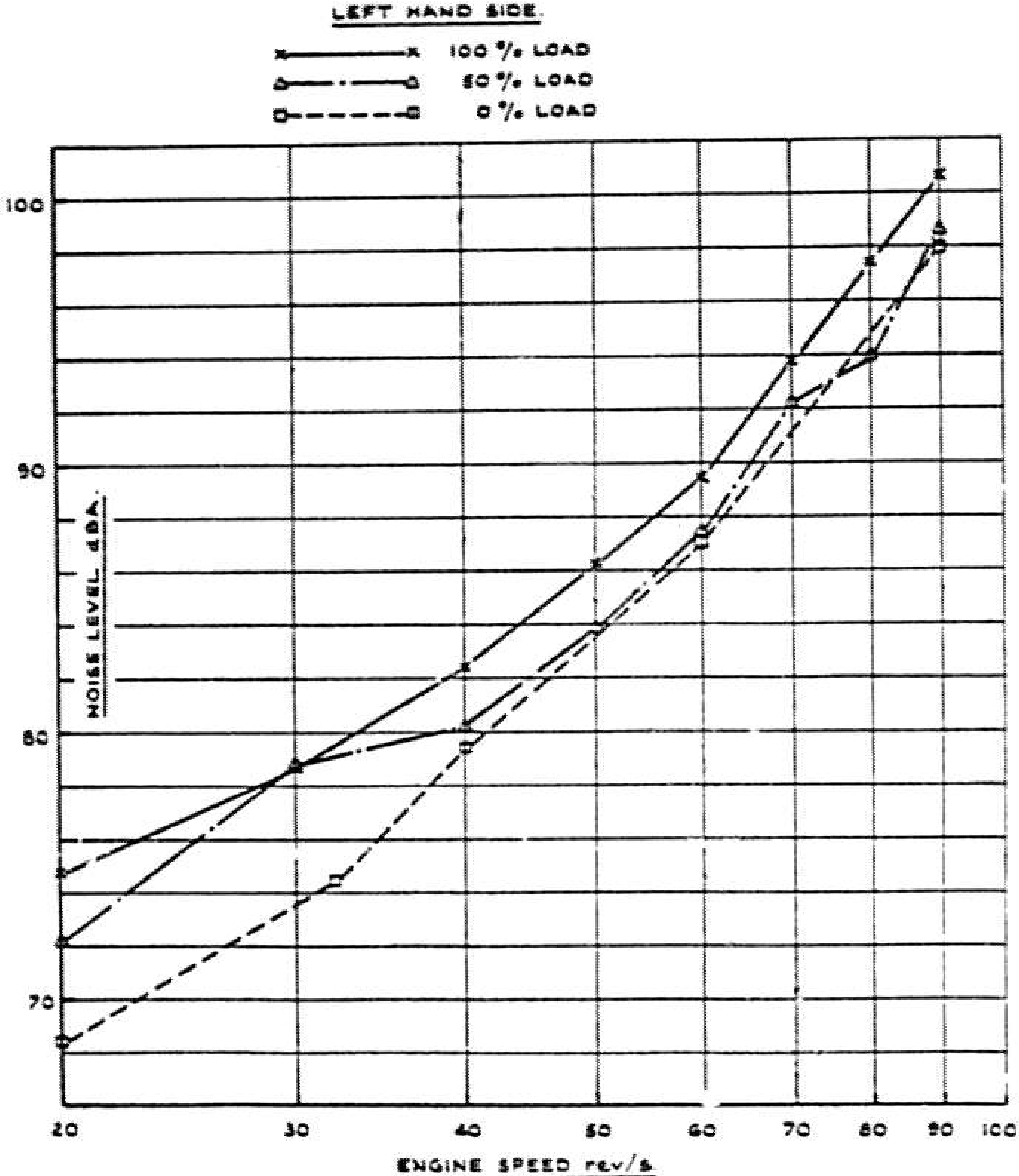


FIGURE 4-8. NOISE LEVELS OVER SPEED RANGE AT 0, 50 AND 100% LOAD

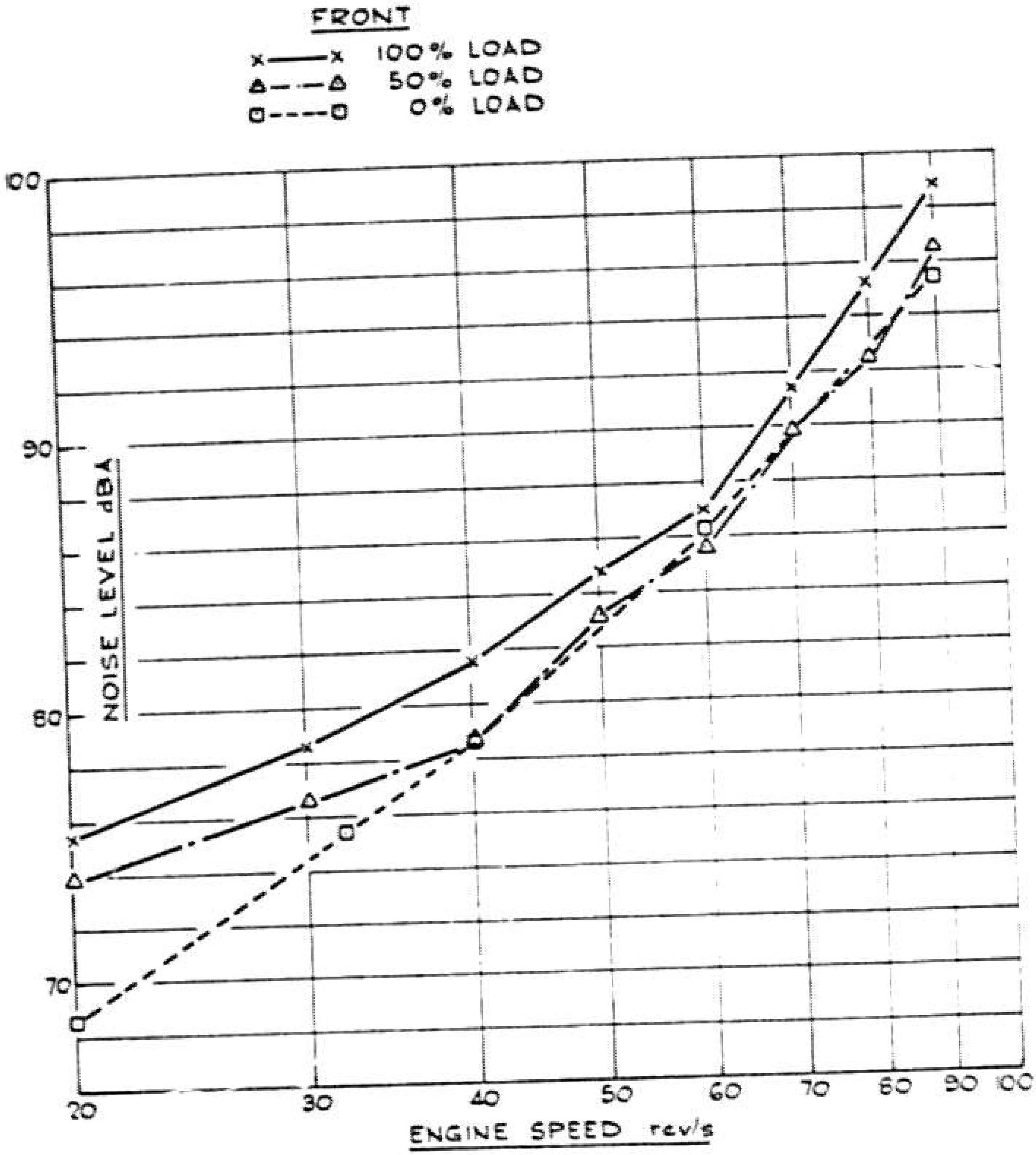


FIGURE 4-9. SOUND PRESSURE LEVELS OVER SPEED RANGE AT 0, 50 AND 100% LOAD

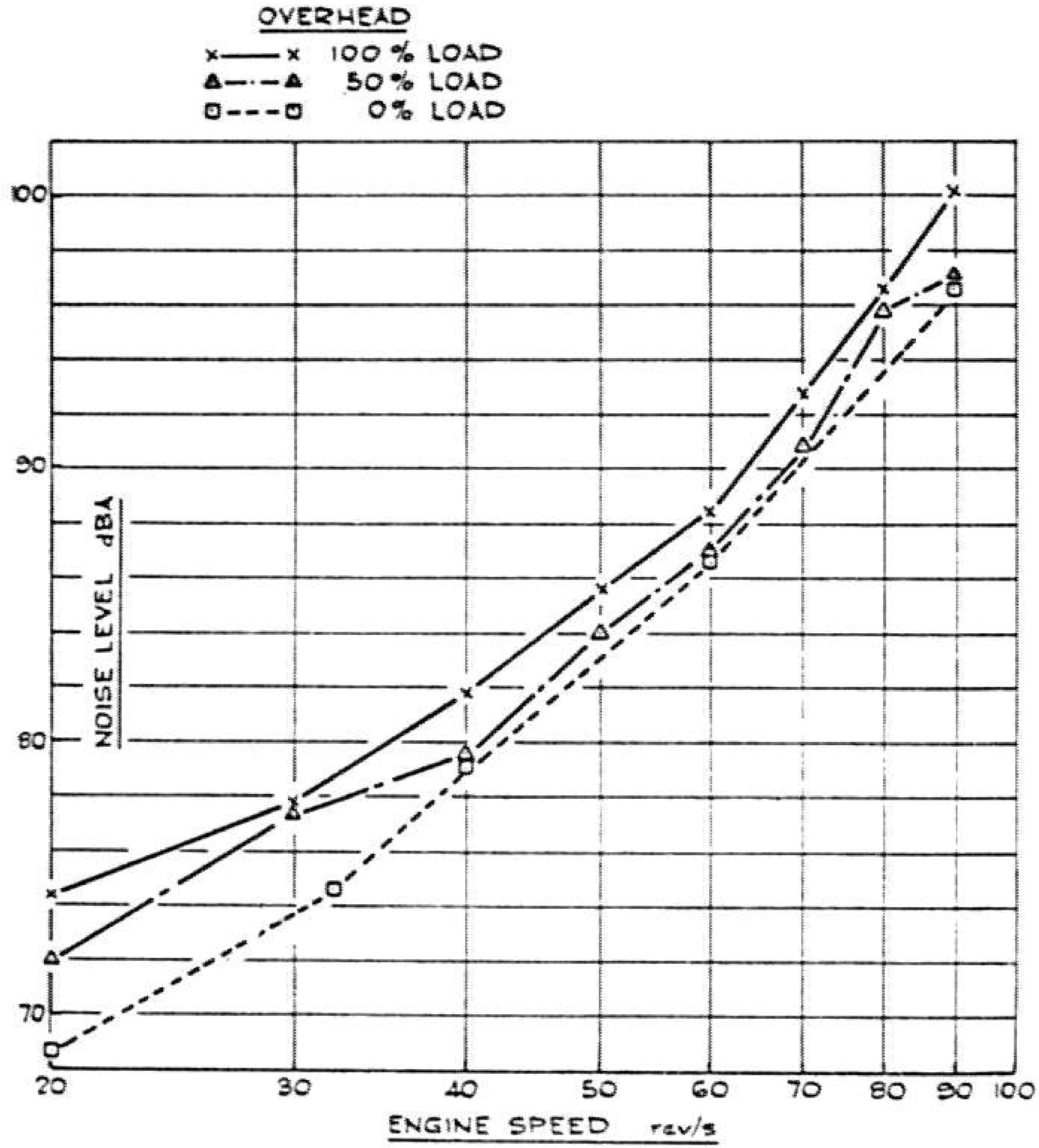


FIGURE 4-10. SOUND PRESSURE LEVELS OVER SPEED RANGE AT 0, 50 AND 100% LOAD

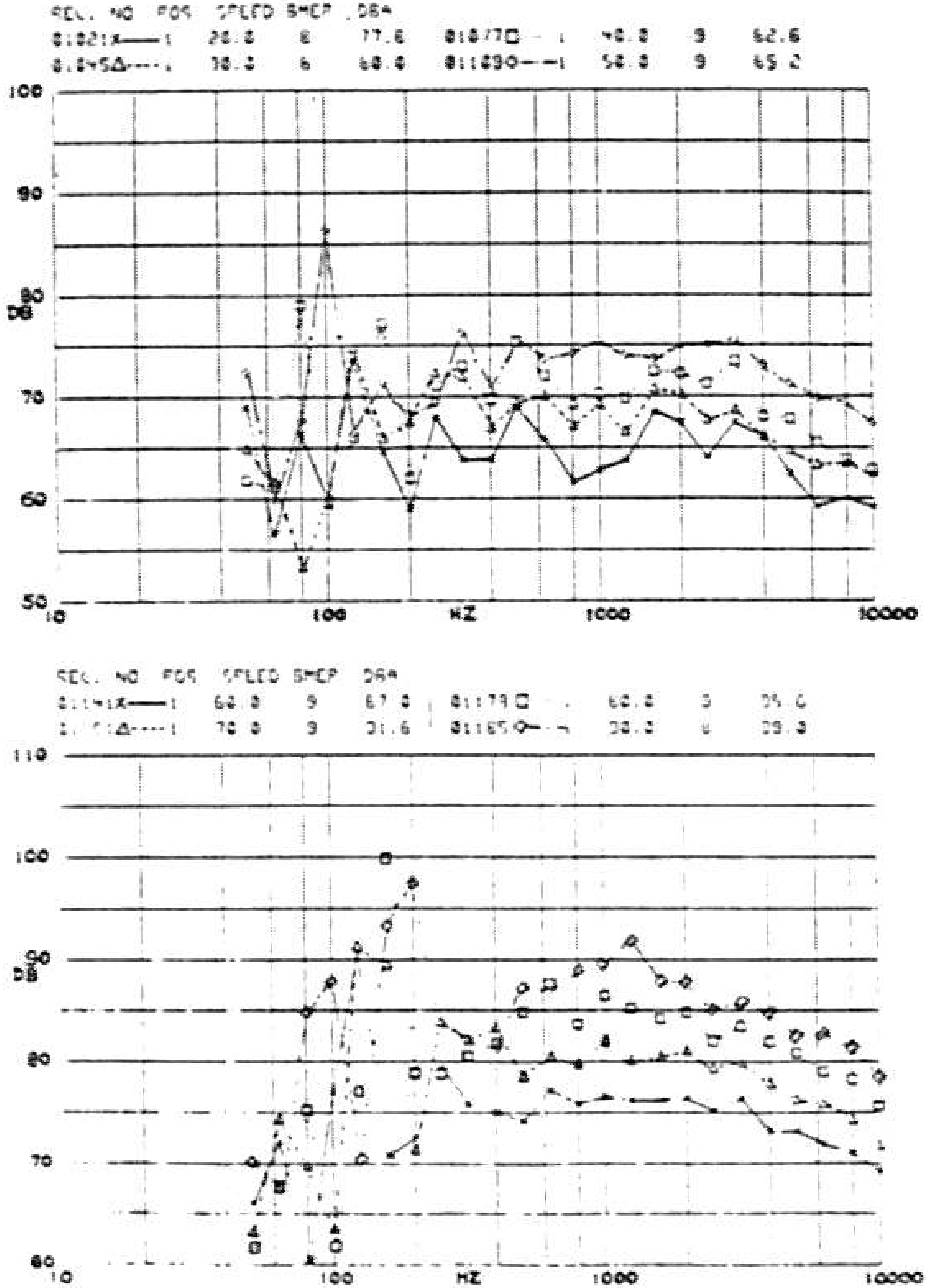
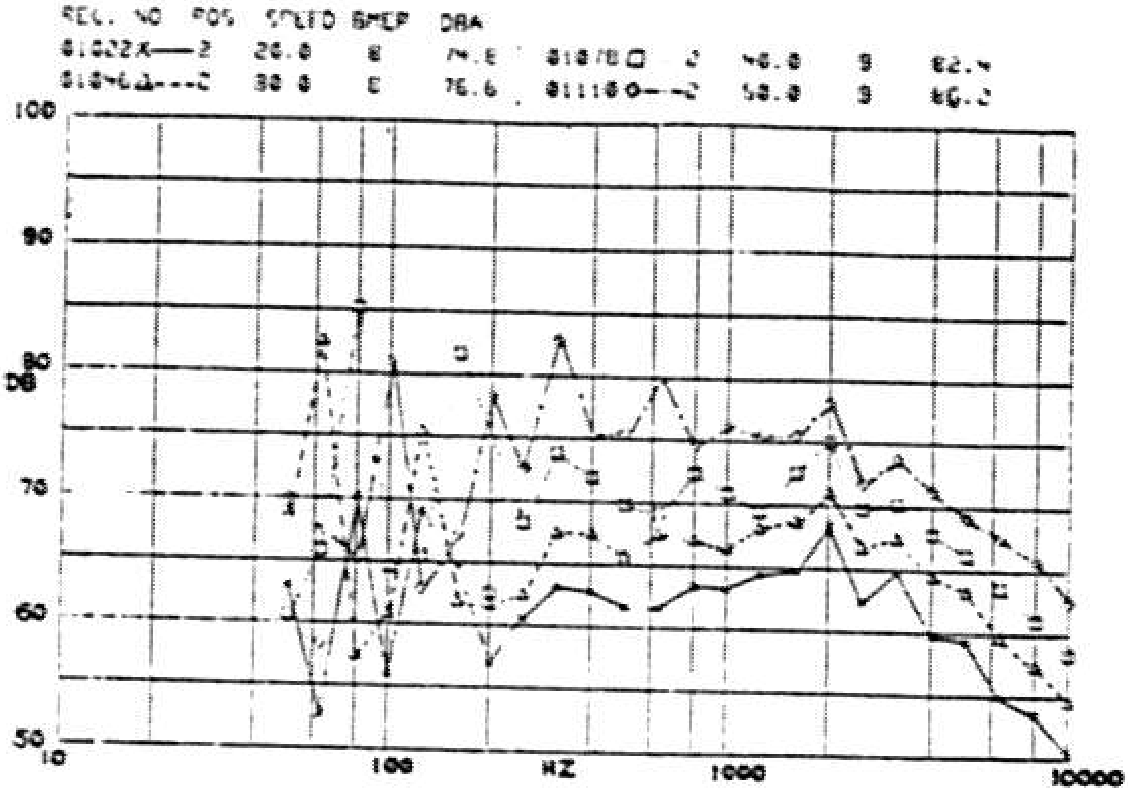


FIGURE 4-11. EFFECT OF SPEED: FULL LOAD
MICROPHONE 1 RIGHT HAND SIDE



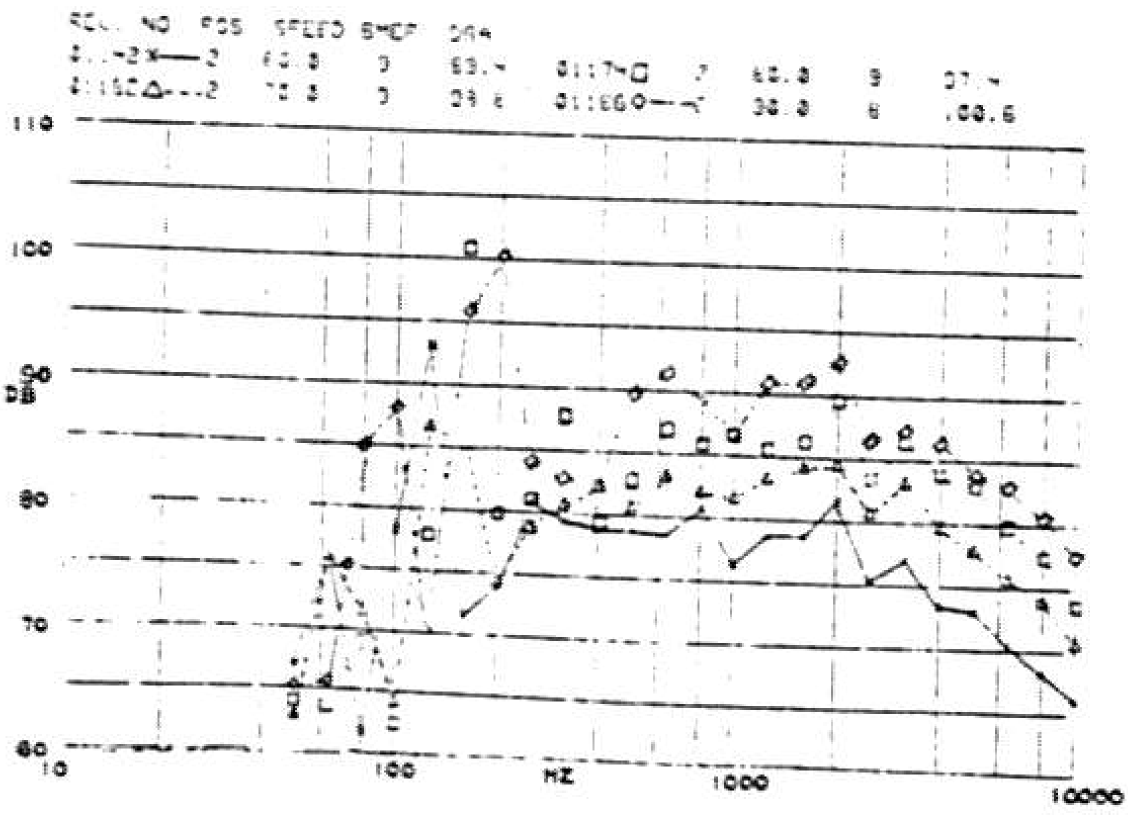


FIGURE 4-12. EFFECT OF SPEED: FULL LOAD
MICROPHONE 2 LEFT HAND SIDE

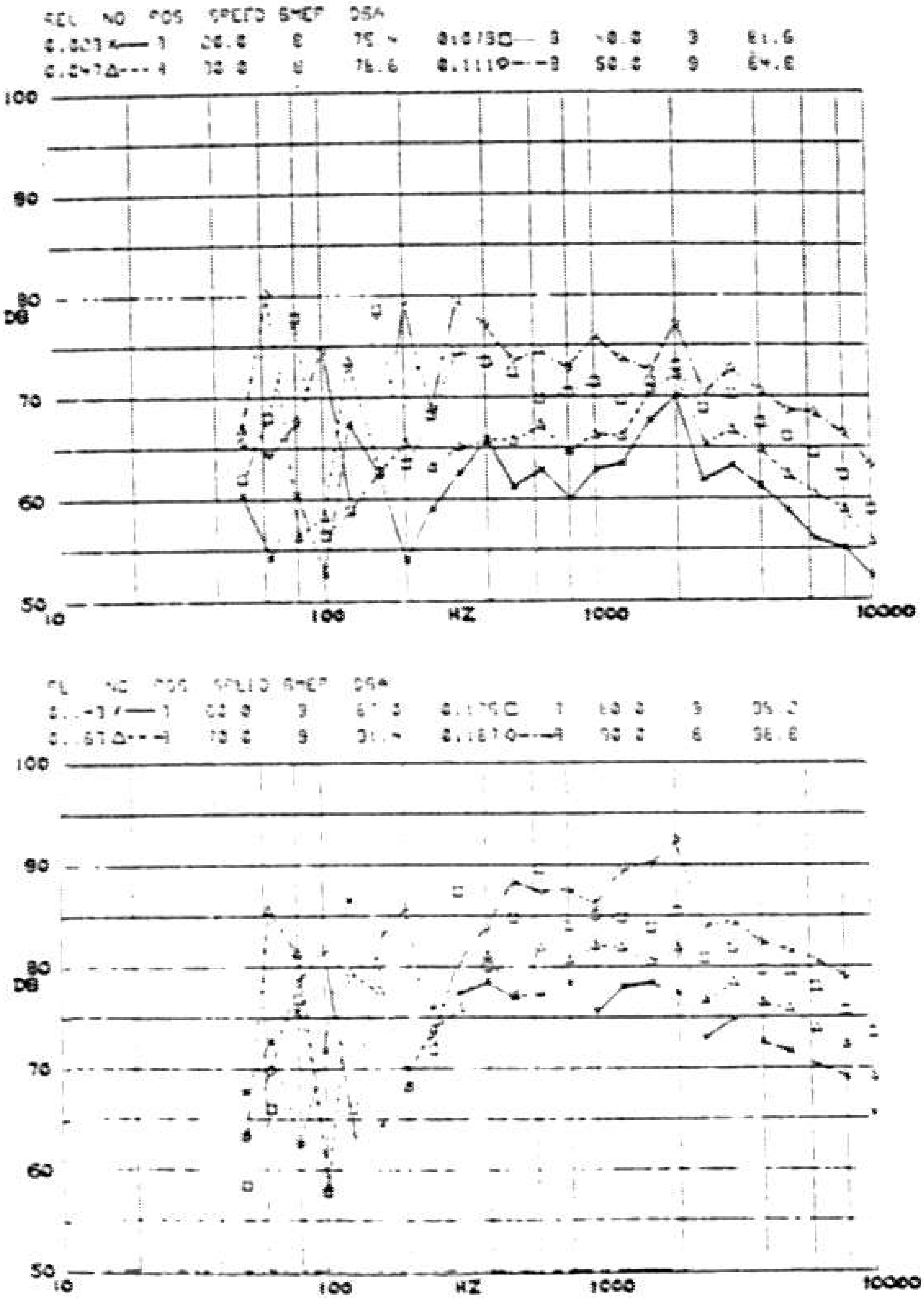


FIGURE 4-13. EFFECT OF SPEED: FULL LOAD
MICROPHONE 3 FRONT

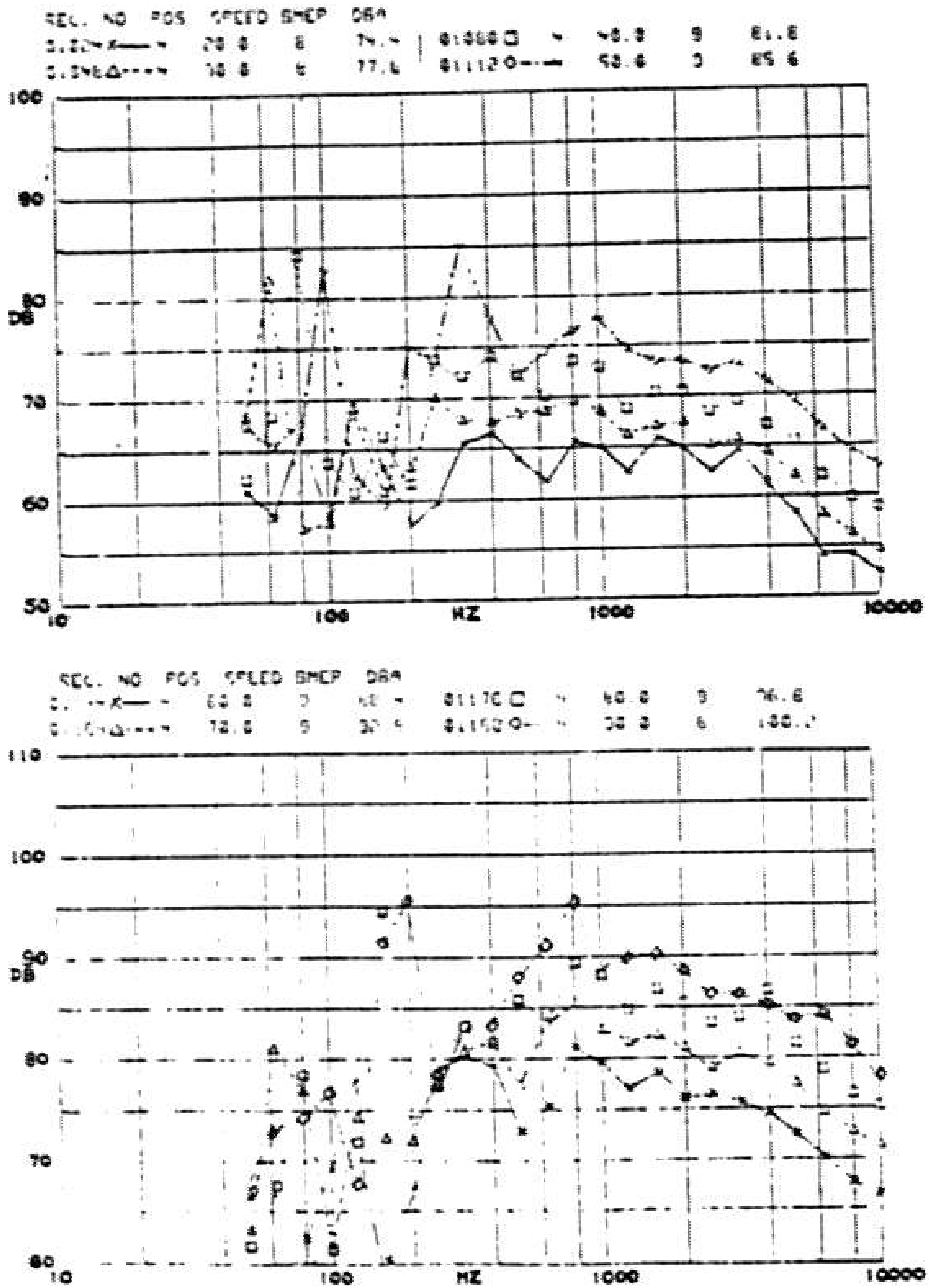
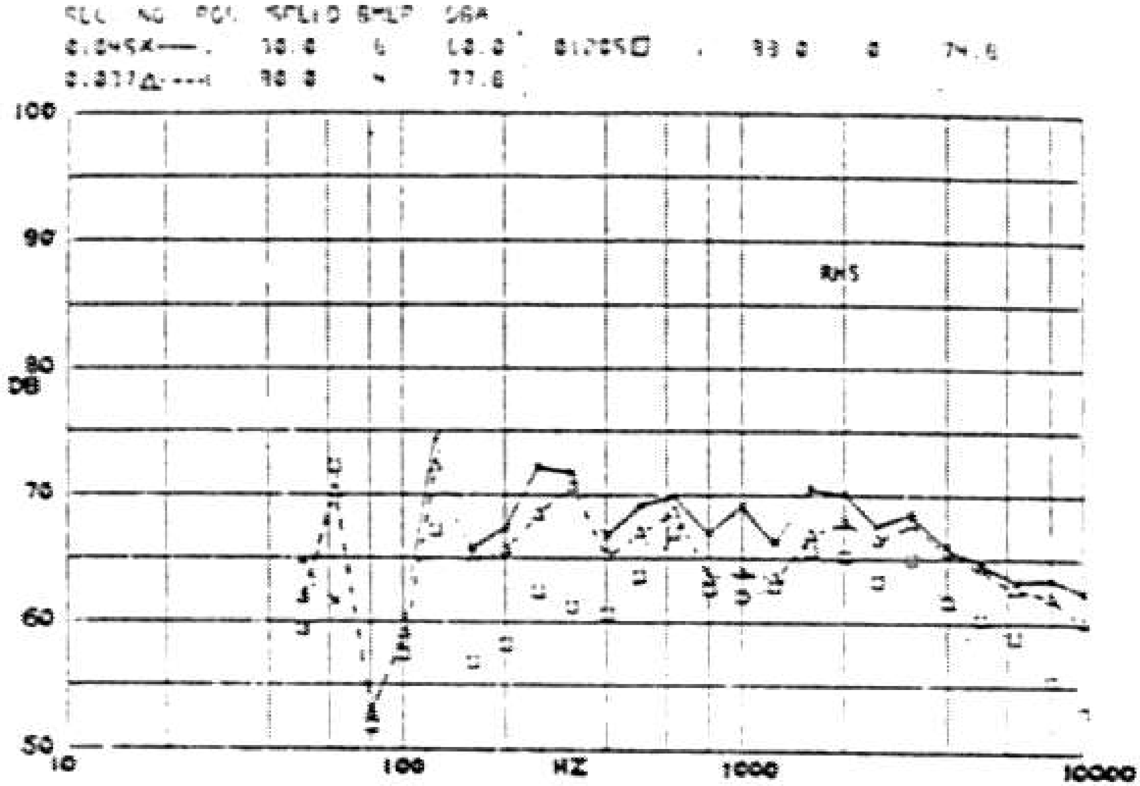


FIGURE 4-14. EFFECT OF SPEED: FULL LOAD
MICROPHONE 4 OVERHEAD



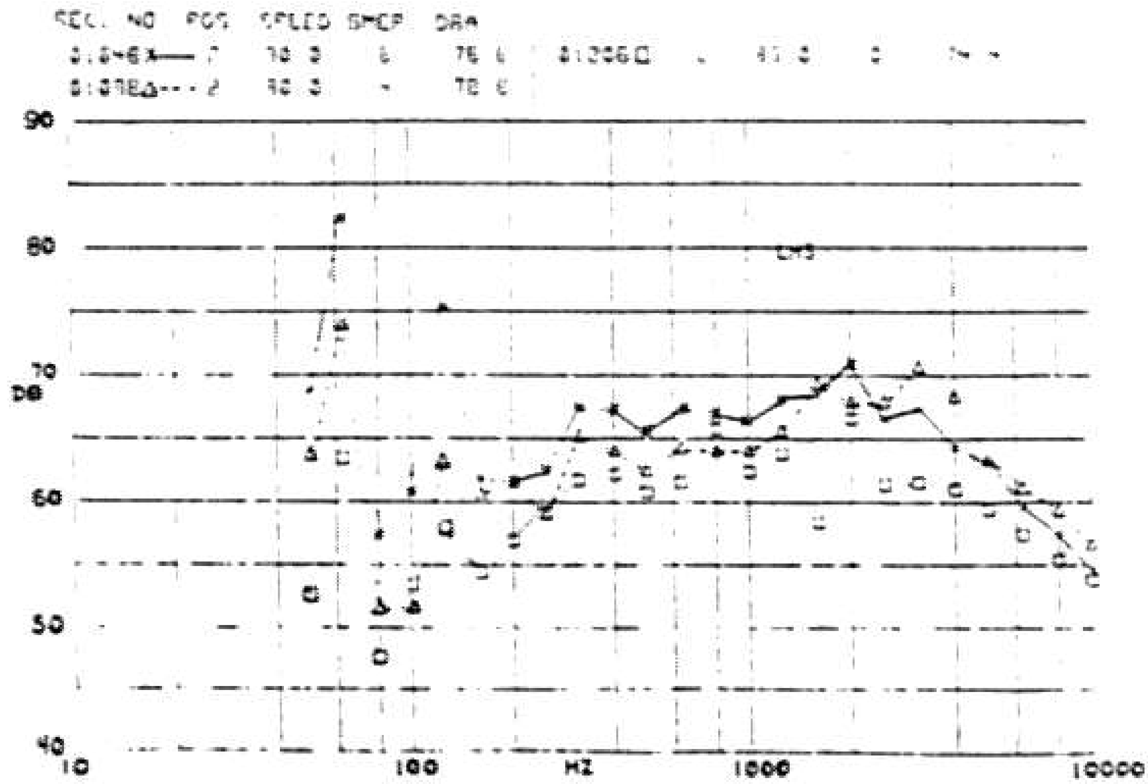
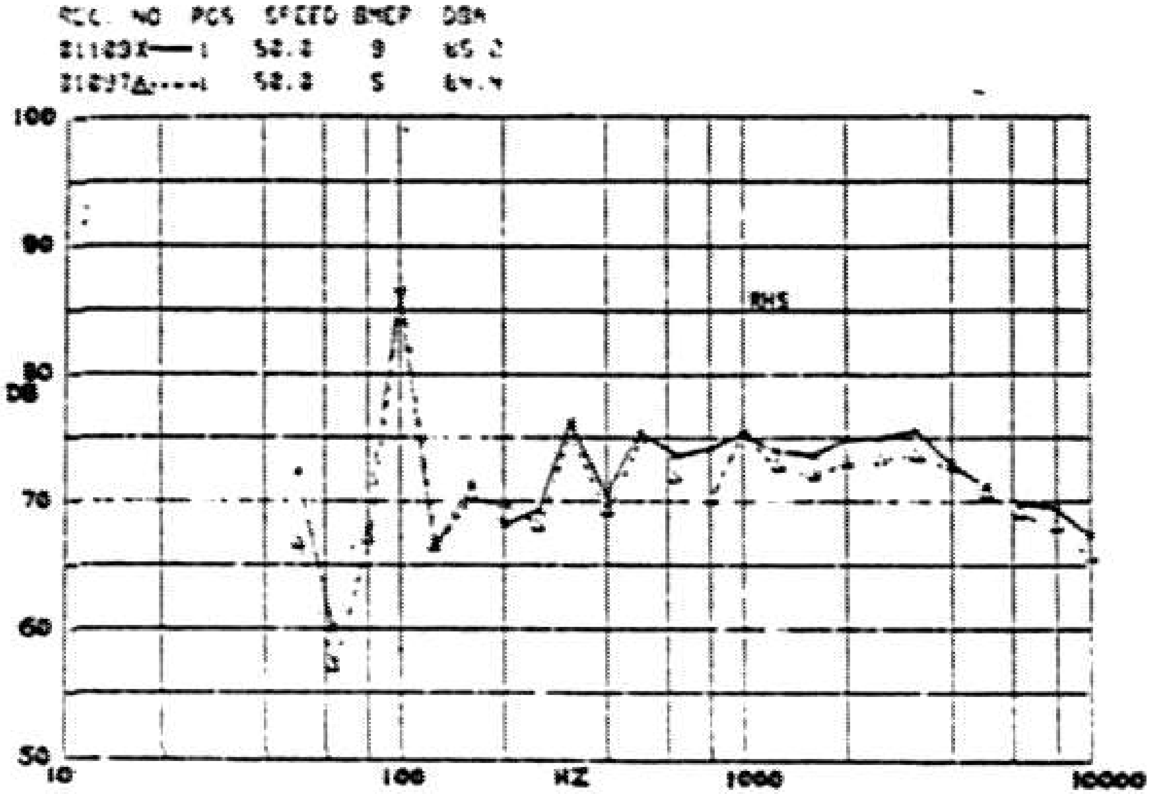


FIGURE 4-15. EFFECT OF LOAD: 30 REV/S



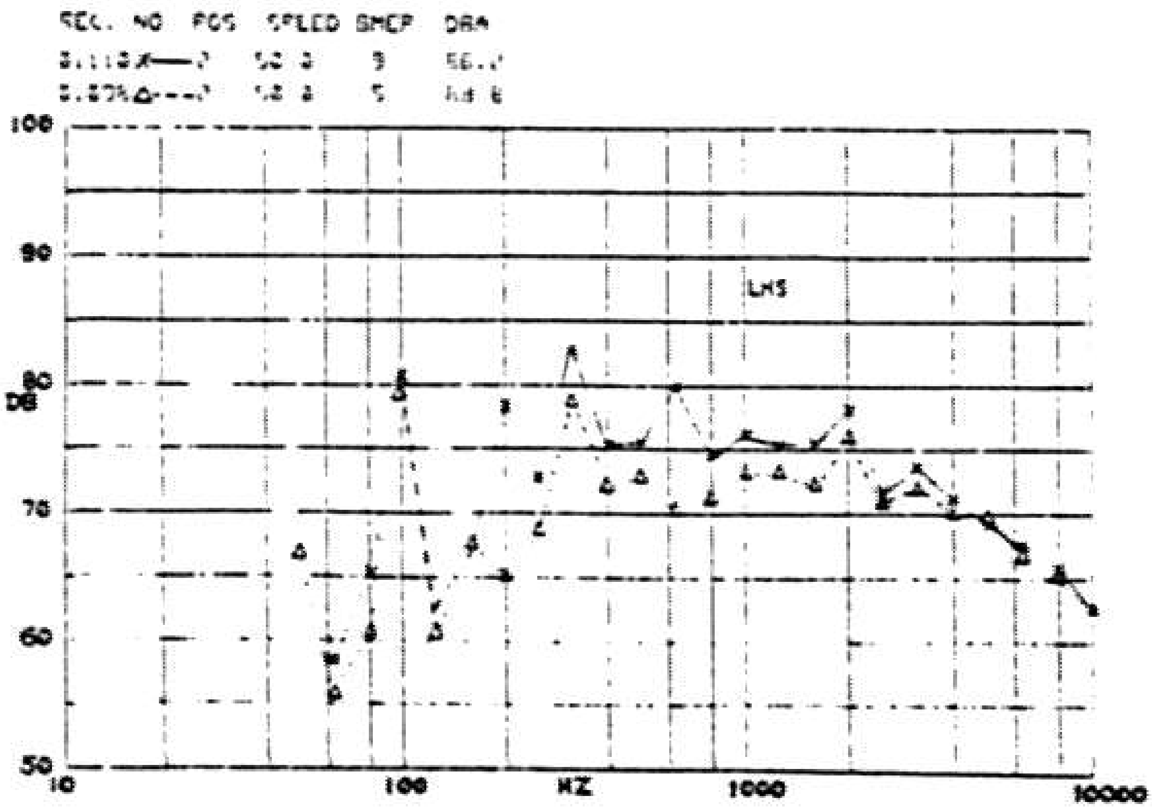


FIGURE 4-16. EFFECT OF LOAD: 50 REV/S

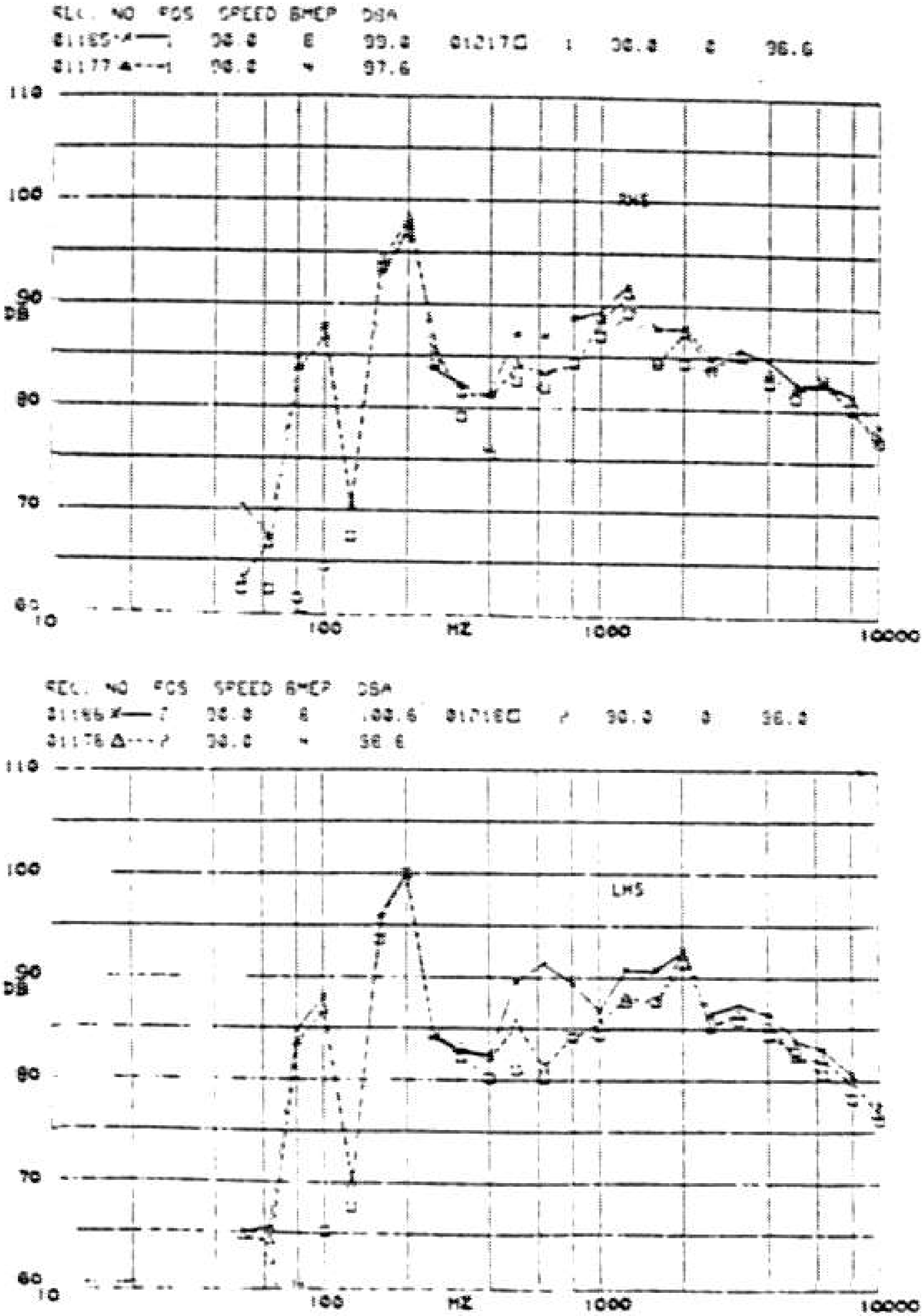


FIGURE 4-17. EFFECT OF LOAD: 90 REV/S

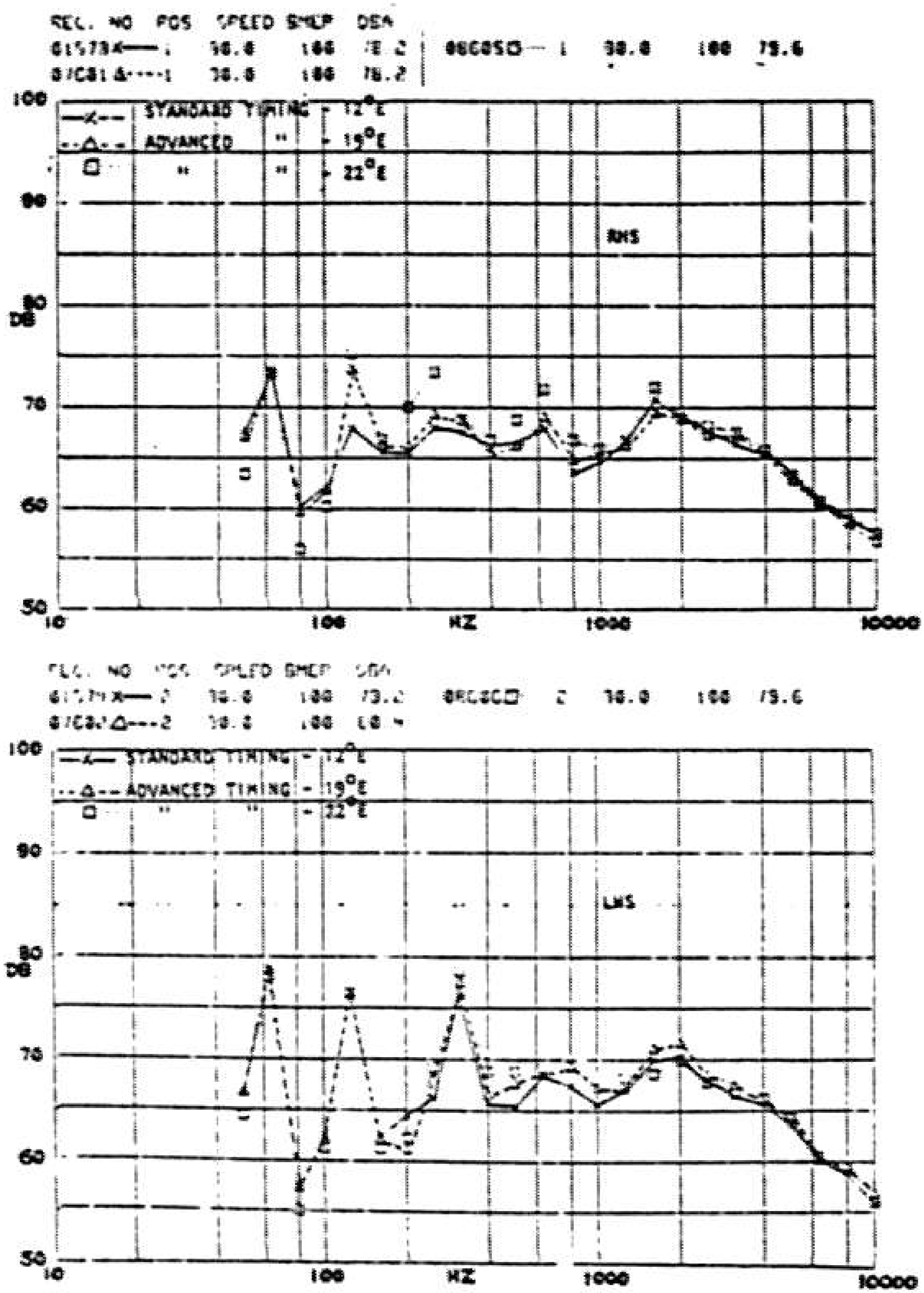
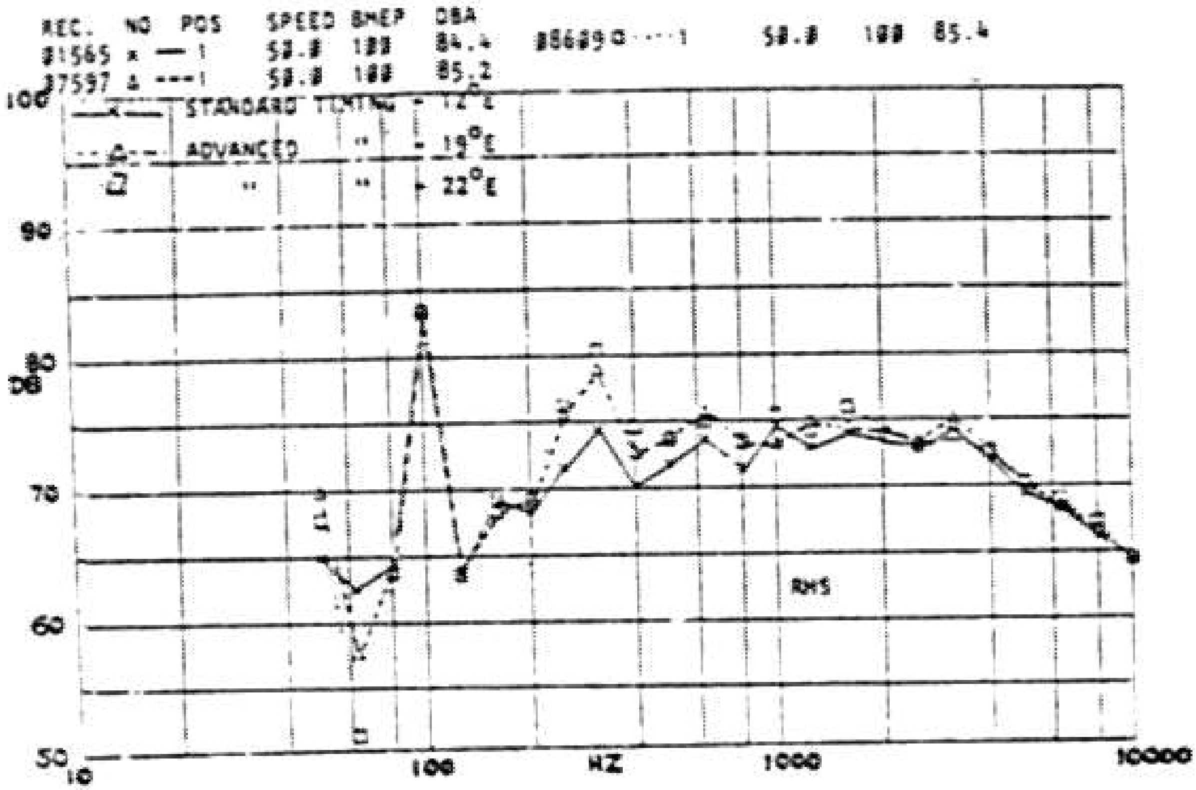


FIGURE 4-18. EFFECT OF TIMING: FULL LOAD 30 REV/S



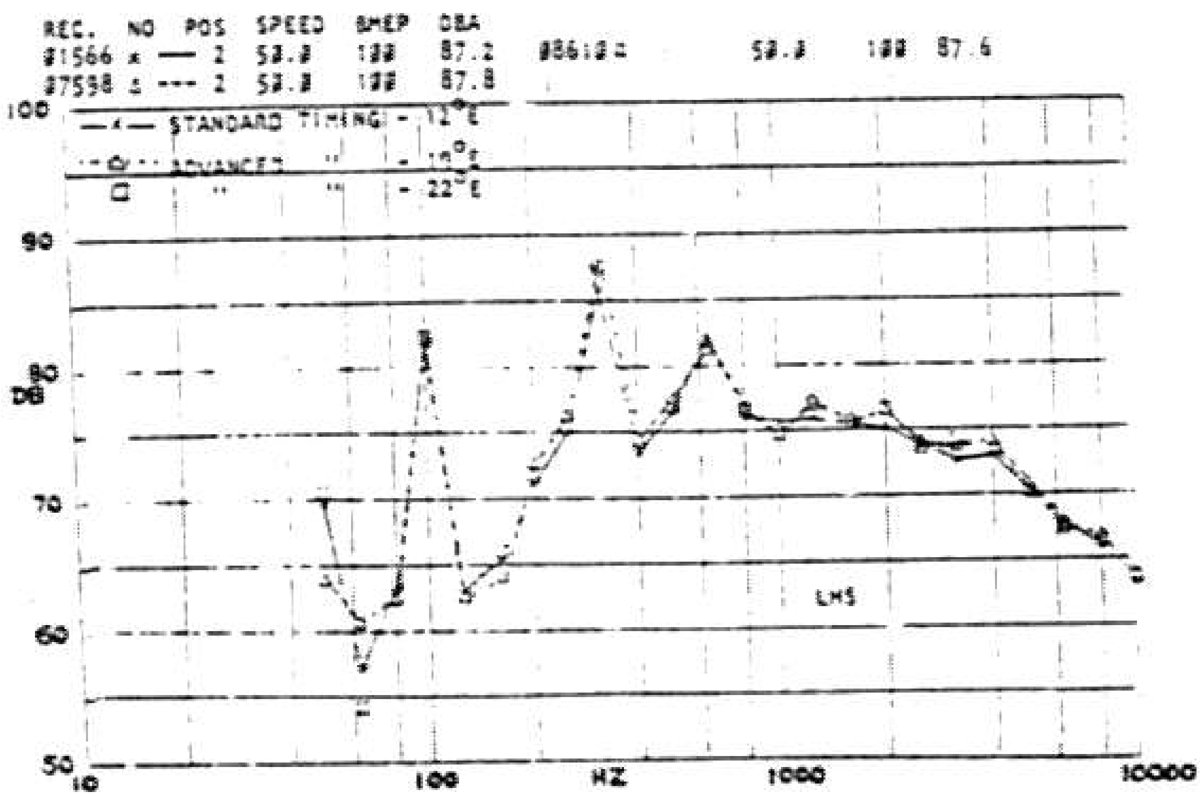
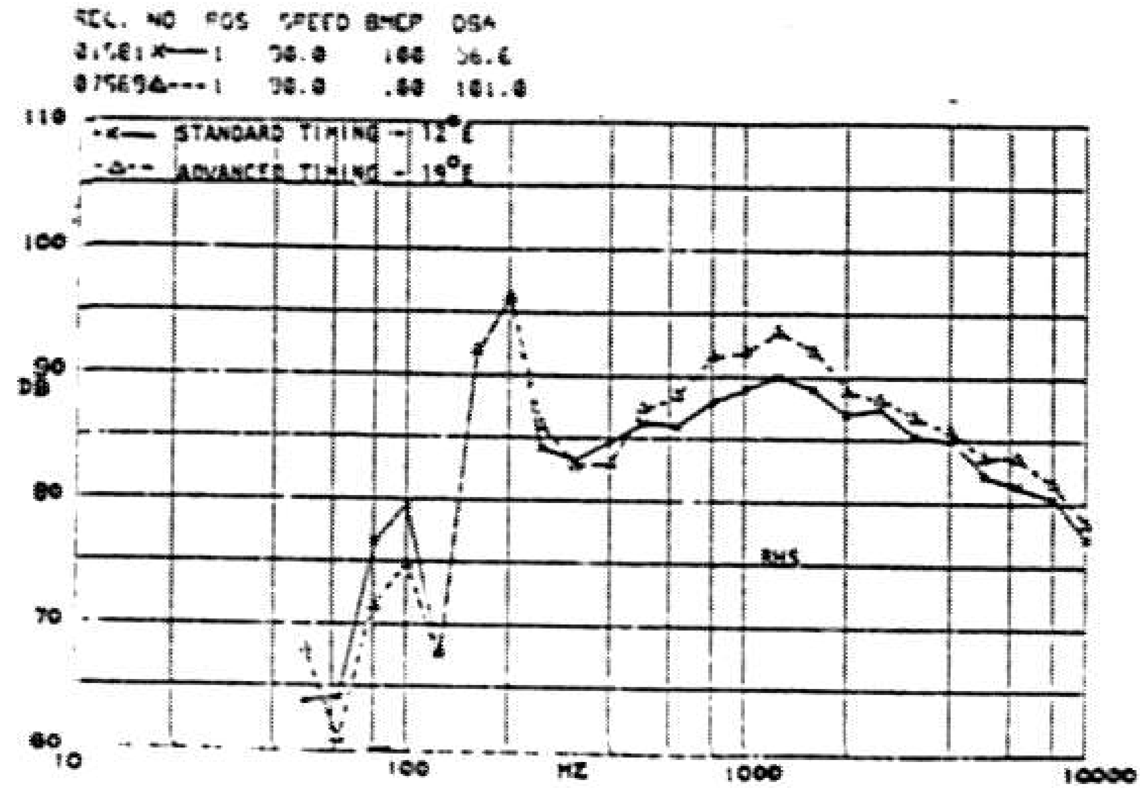


FIGURE 4-19. EFFECT OF TIMING: FULL LOAD 50 REV/S



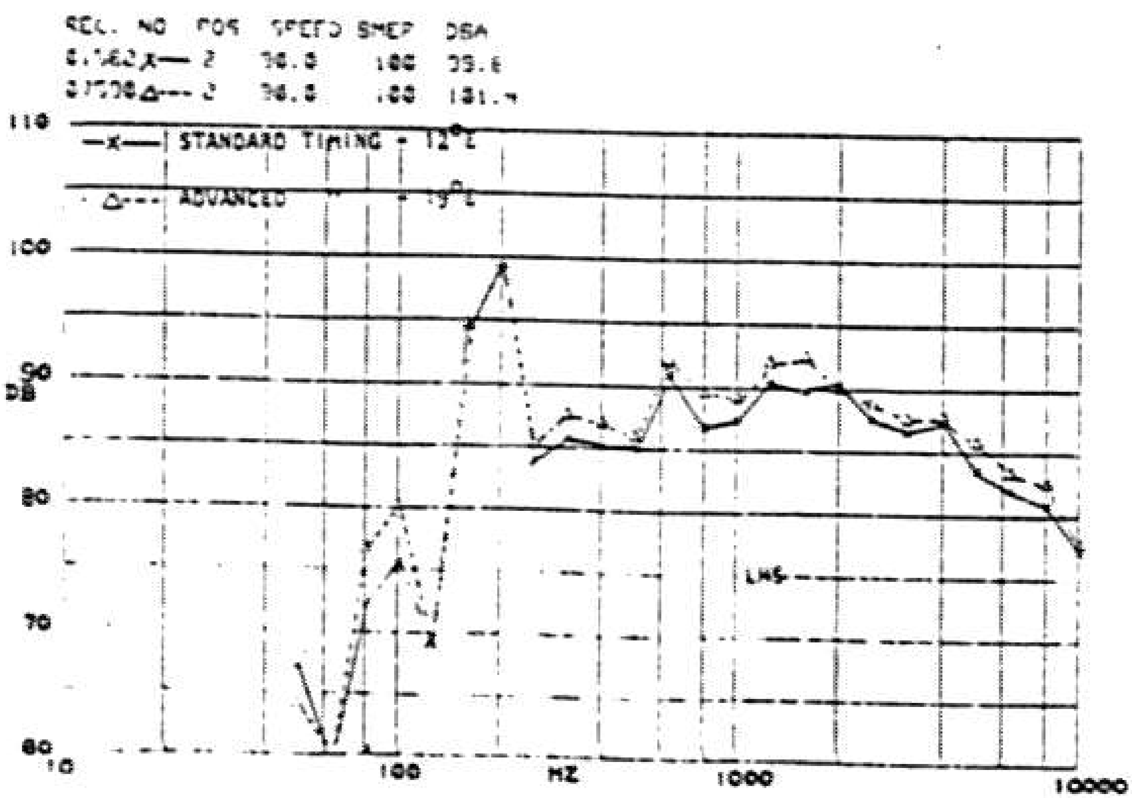


FIGURE 4-20. EFFECT OF TIMING: FULL LOAD 90 REV//S

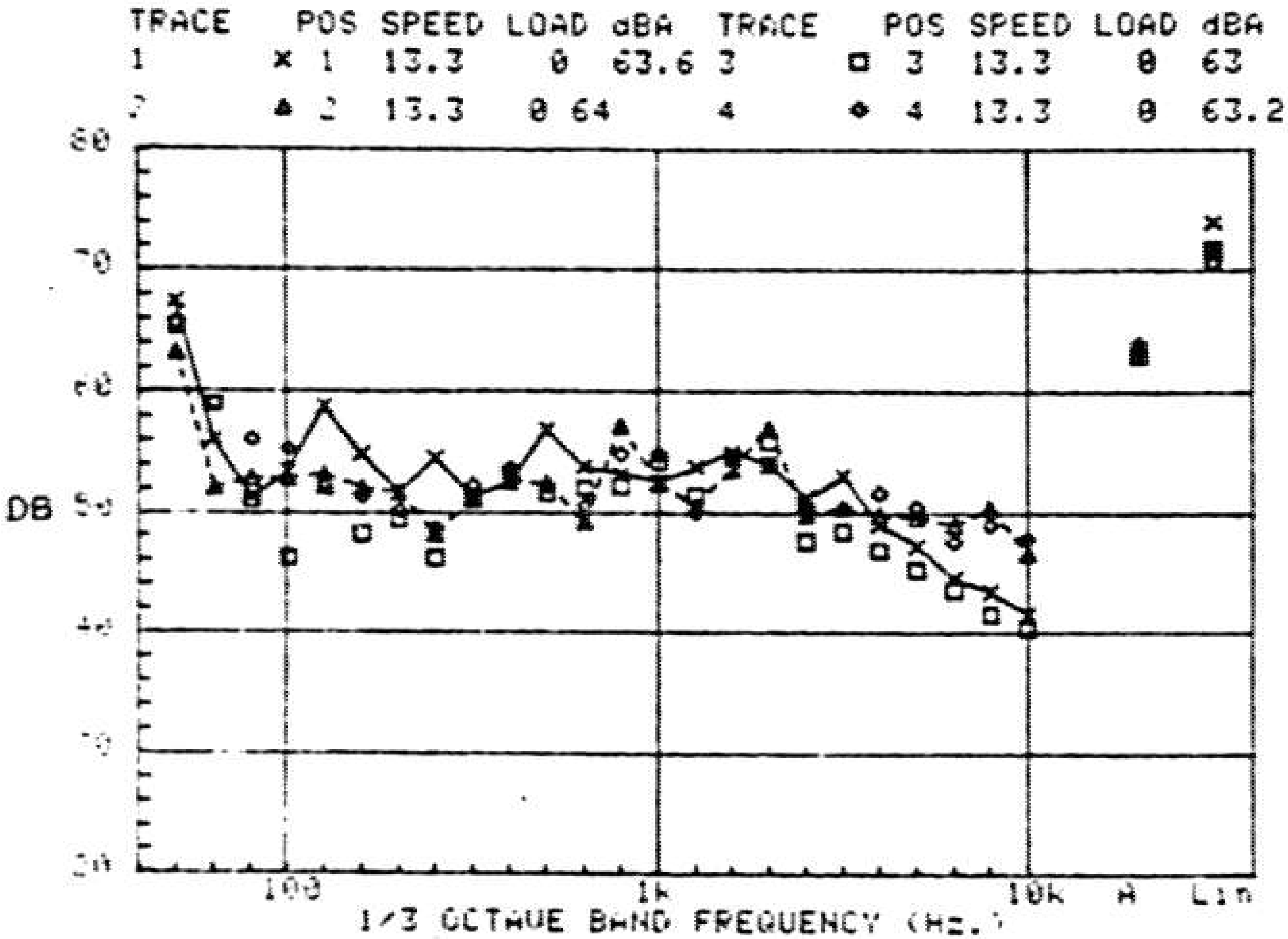


FIGURE 4-21. IDLE NOISE SPECTRA (ENGINE HOT)
MICROPHONE POSITIONS 1, 2, 3, AND 4

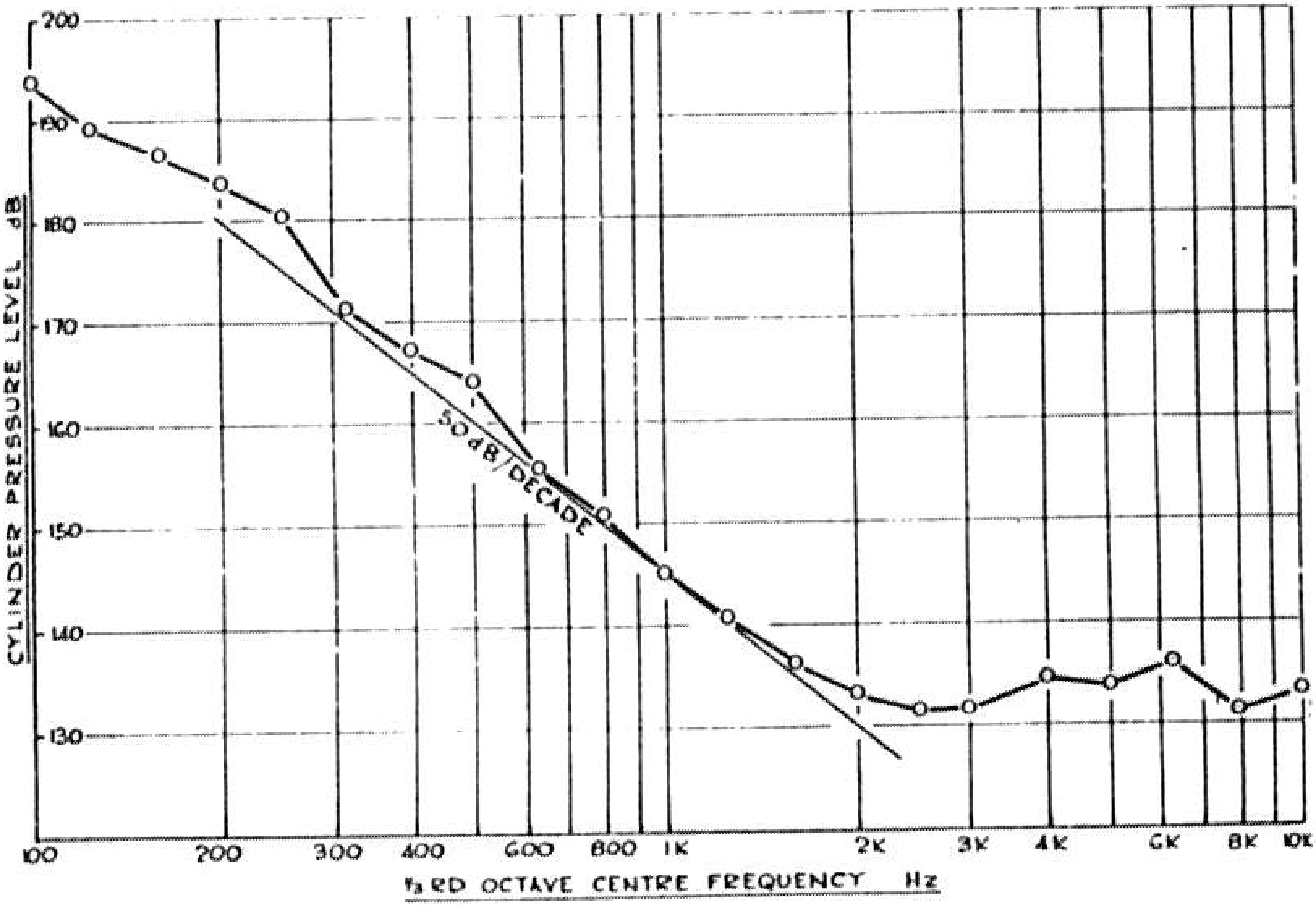


FIGURE 4-22. CYLINDER PRESSURE LEVEL SPECTRUM AT 30 REV/S 100% LOAD

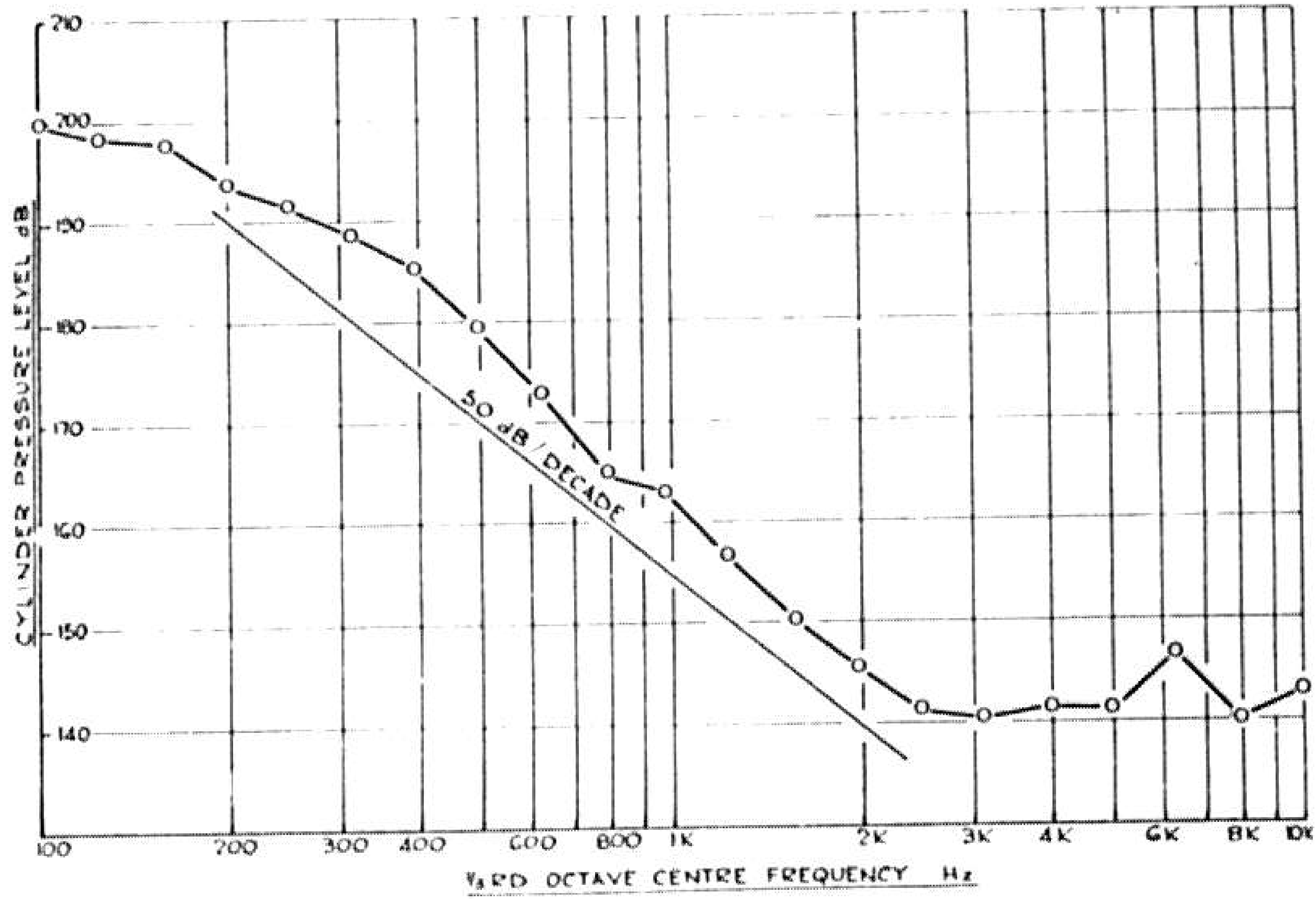


FIGURE 4-23. CYLINDER PRESSURE LEVEL SPECTRUM AT 50 REV/S 100% LOAD

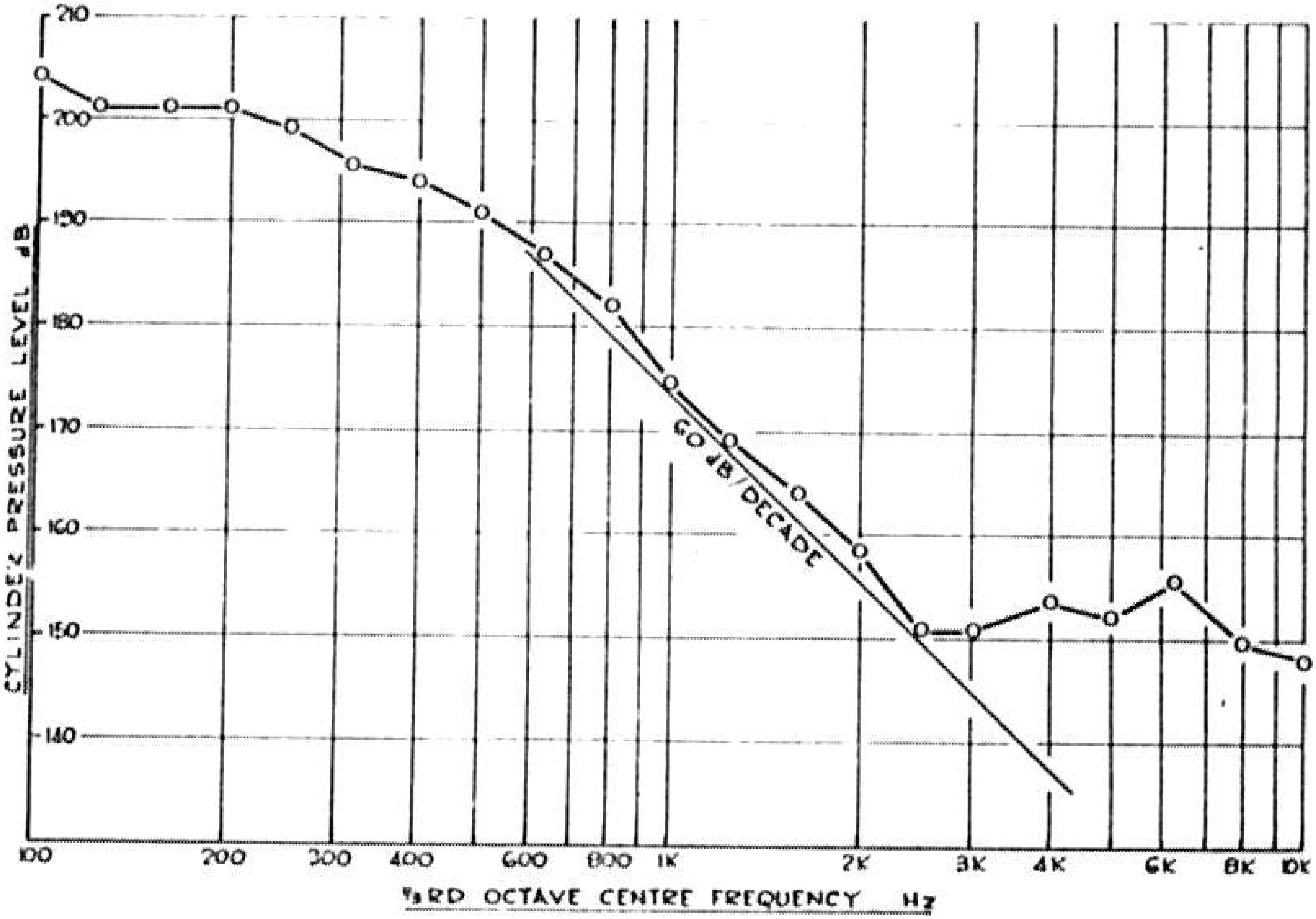


FIGURE 4-24. CYLINDER PRESSURE LEVEL SPECTRUM AT 70 REV/S 100% LOAD

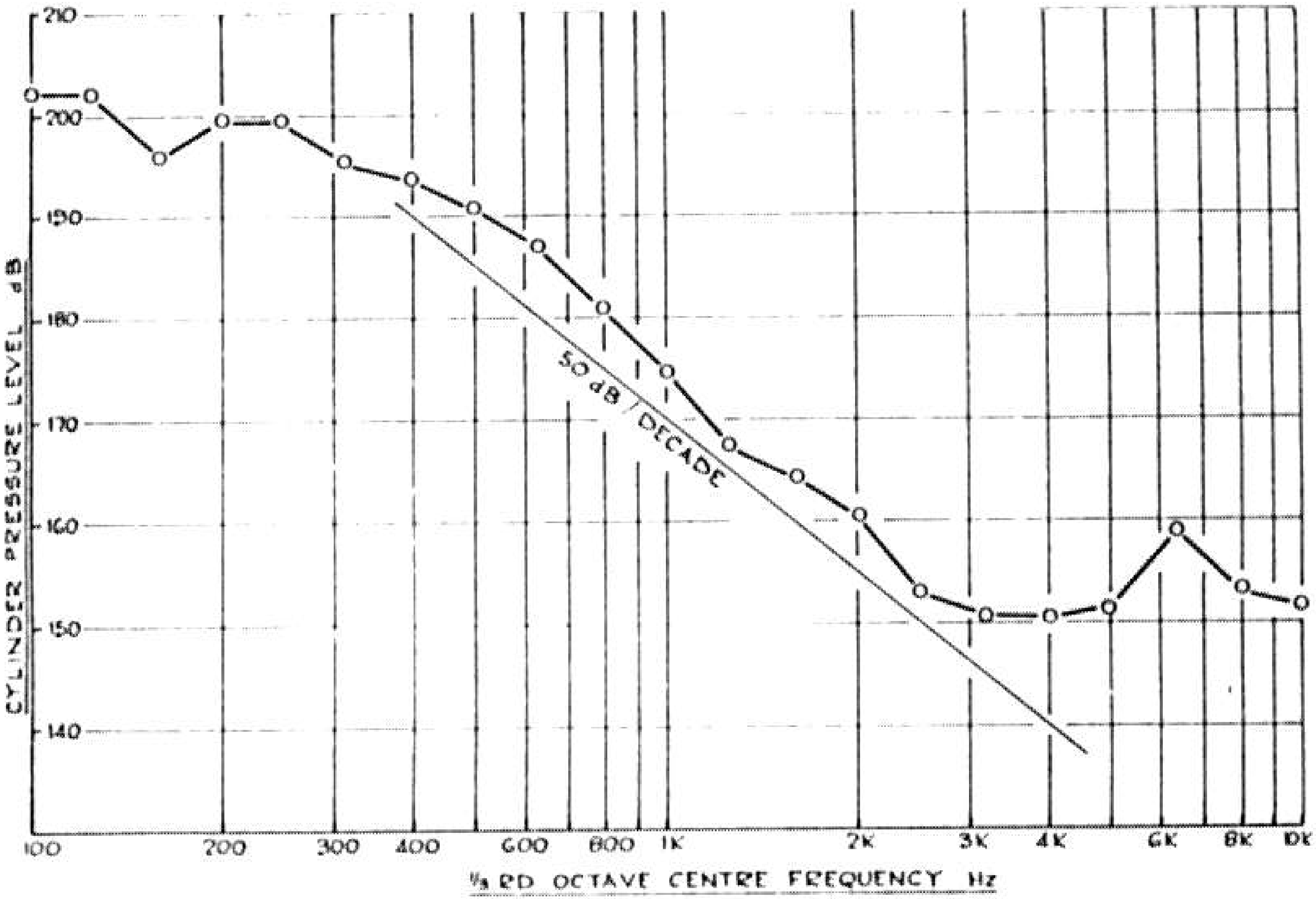


FIGURE 4-25. CYLINDER PRESSURE LEVEL SPECTRUM AT 90 REV/S 100% LOAD

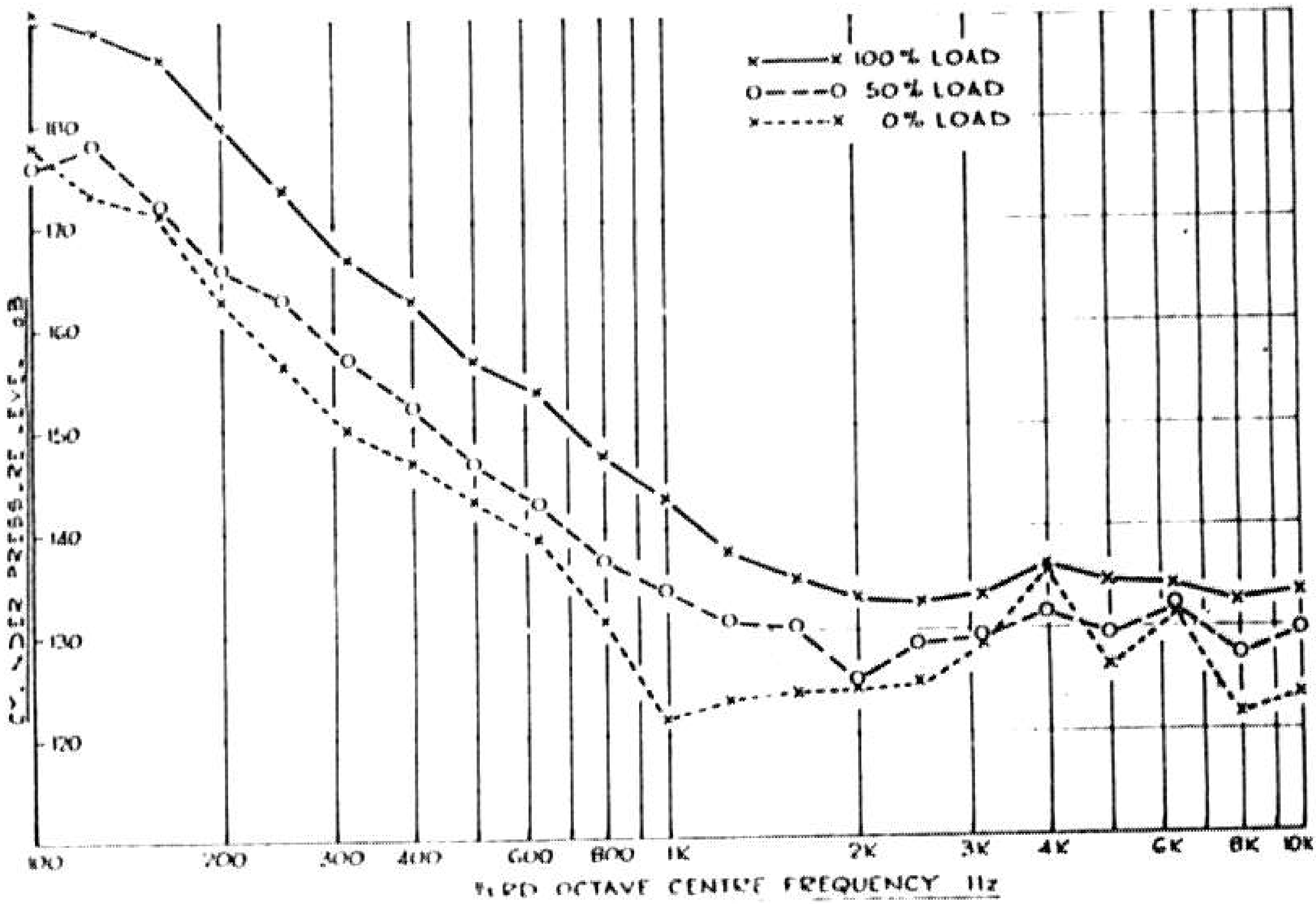


FIGURE 4-26. EFFECT OF LOAD ON CYLINDER PRESSURE SPECTRUM AT 20 REV/S

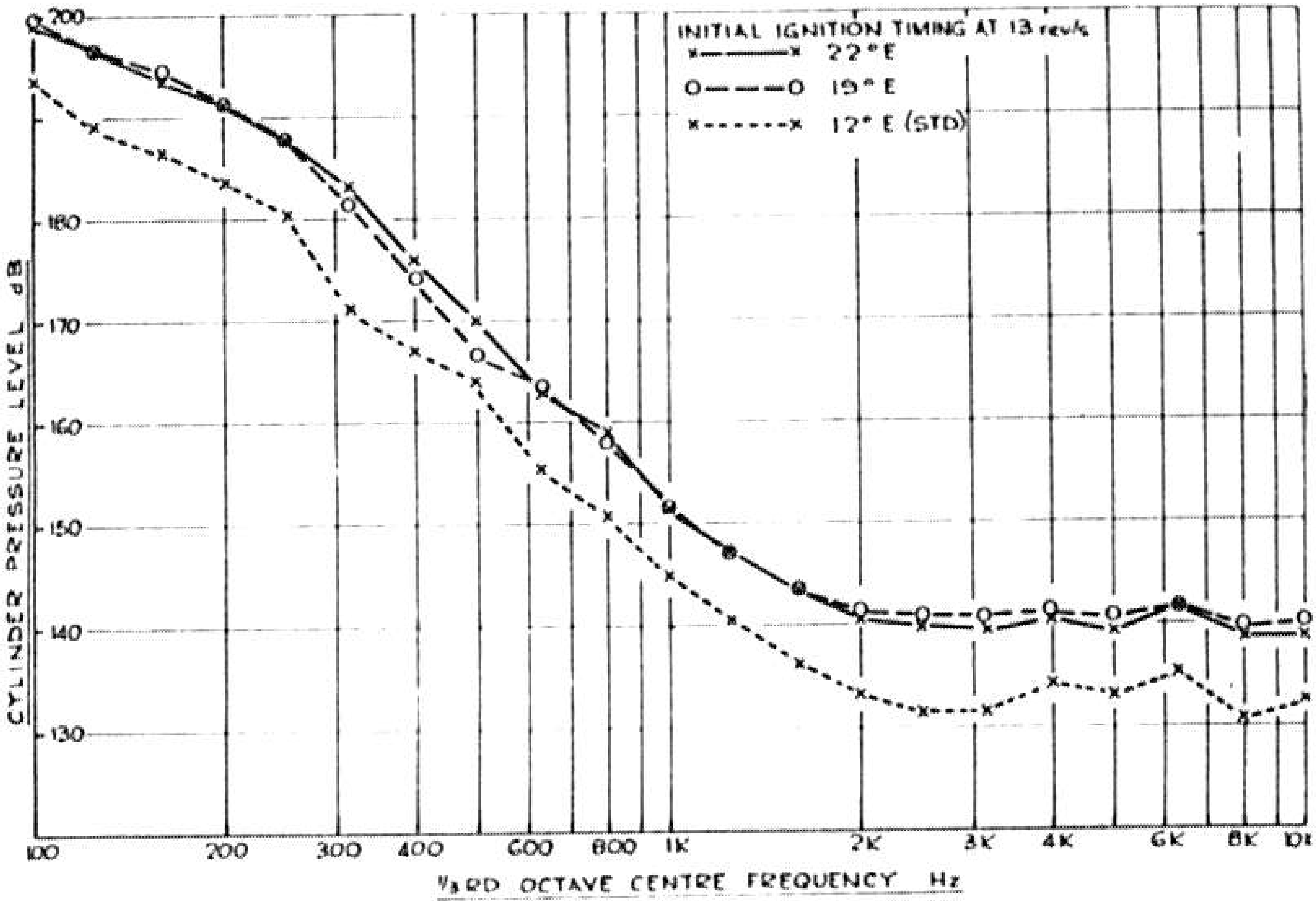


FIGURE 4-27. EFFECT OF IGNITION TIMING ON CYLINDER PRESSURE LEVEL SPECTRUM AT 100% LOAD 30 REV/S

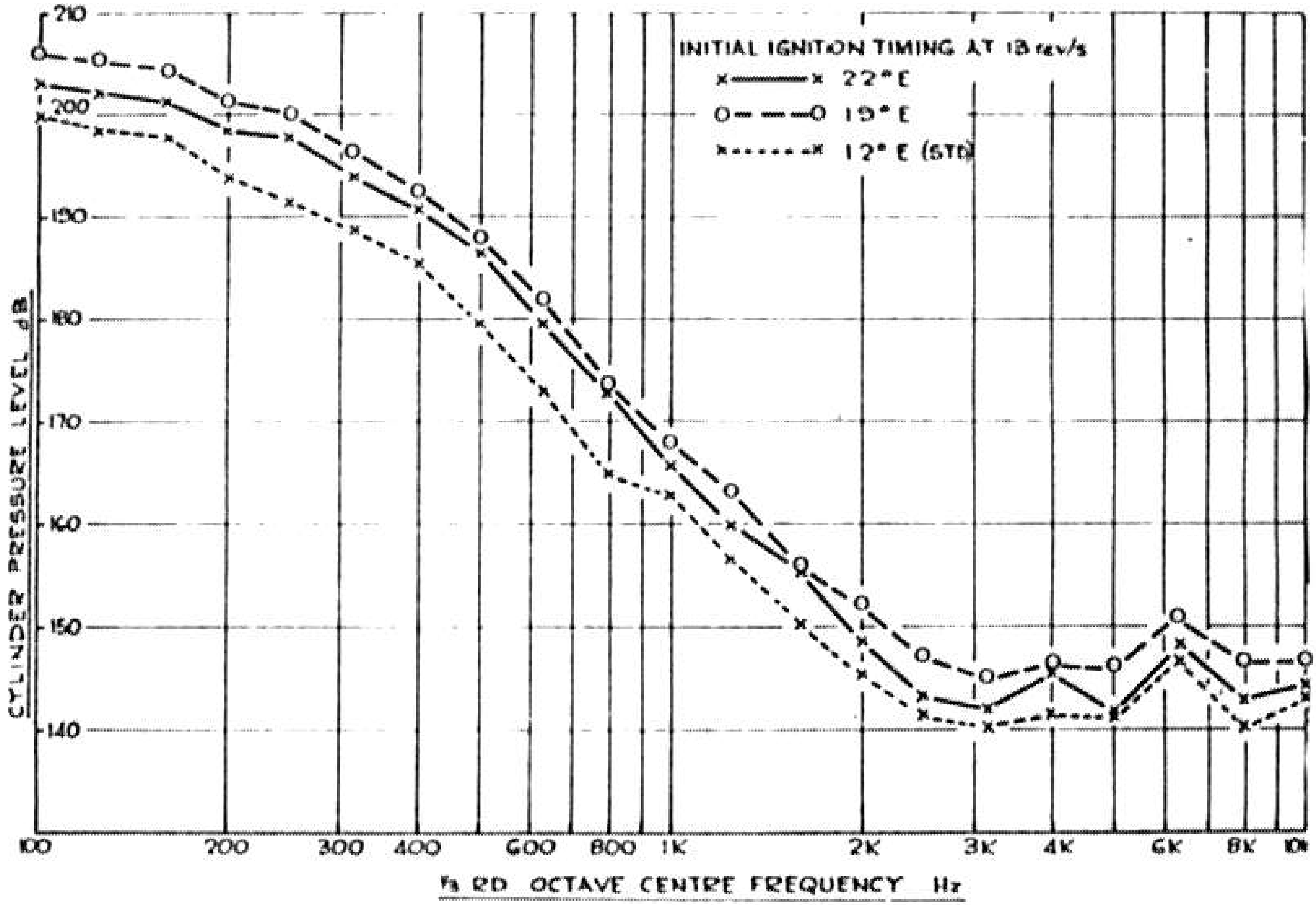


FIGURE 4-28. EFFECT OF IGNITION TIMING ON CYLINDER PRESSURE LEVEL SPECTRUM AT 100% LOAD 50 REV/S

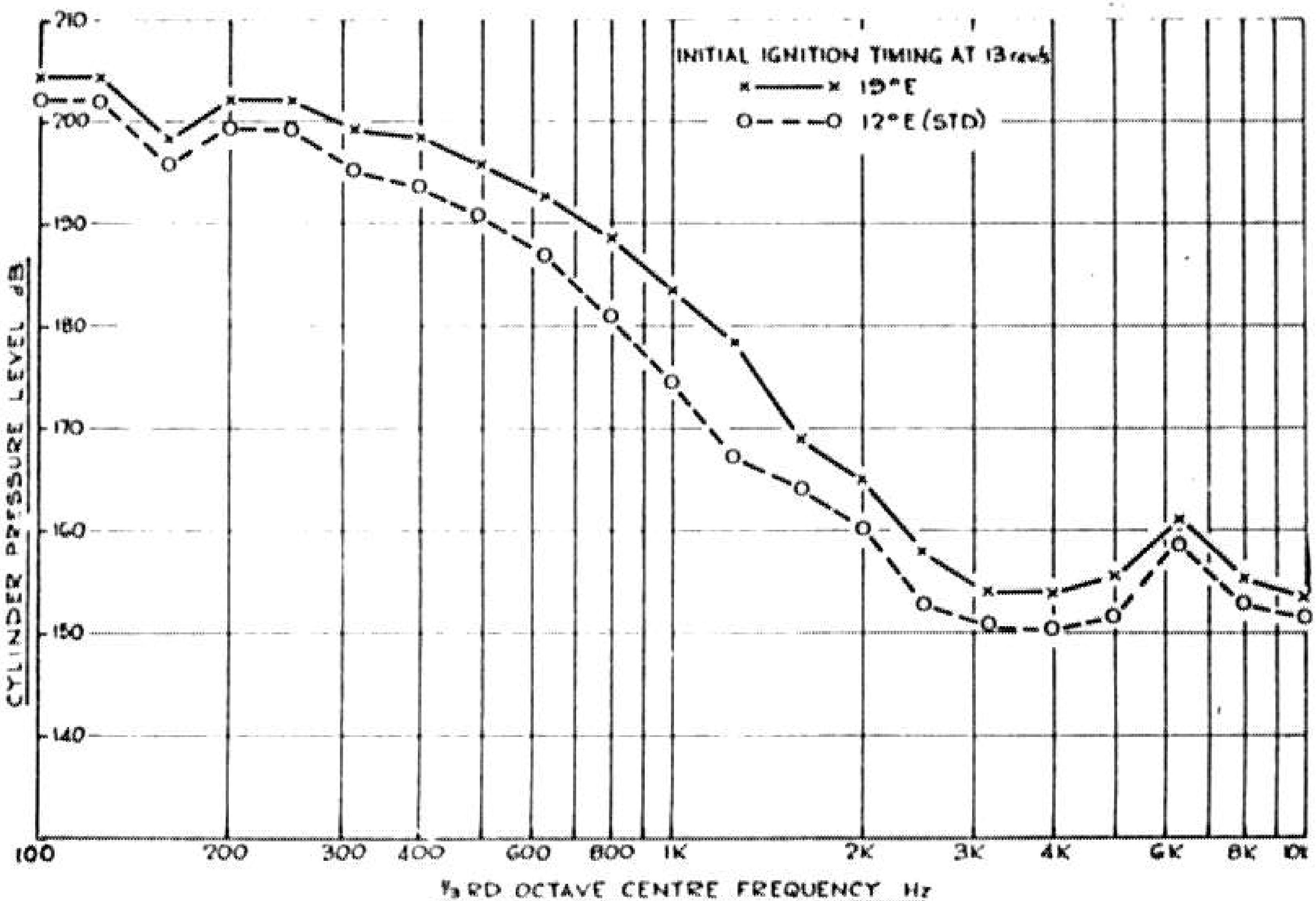


FIGURE 4-29. EFFECT OF IGNITION TIMING ON CYLINDER PRESSURE LEVEL SPECTRUM AT 100% LOAD 90 REV/S

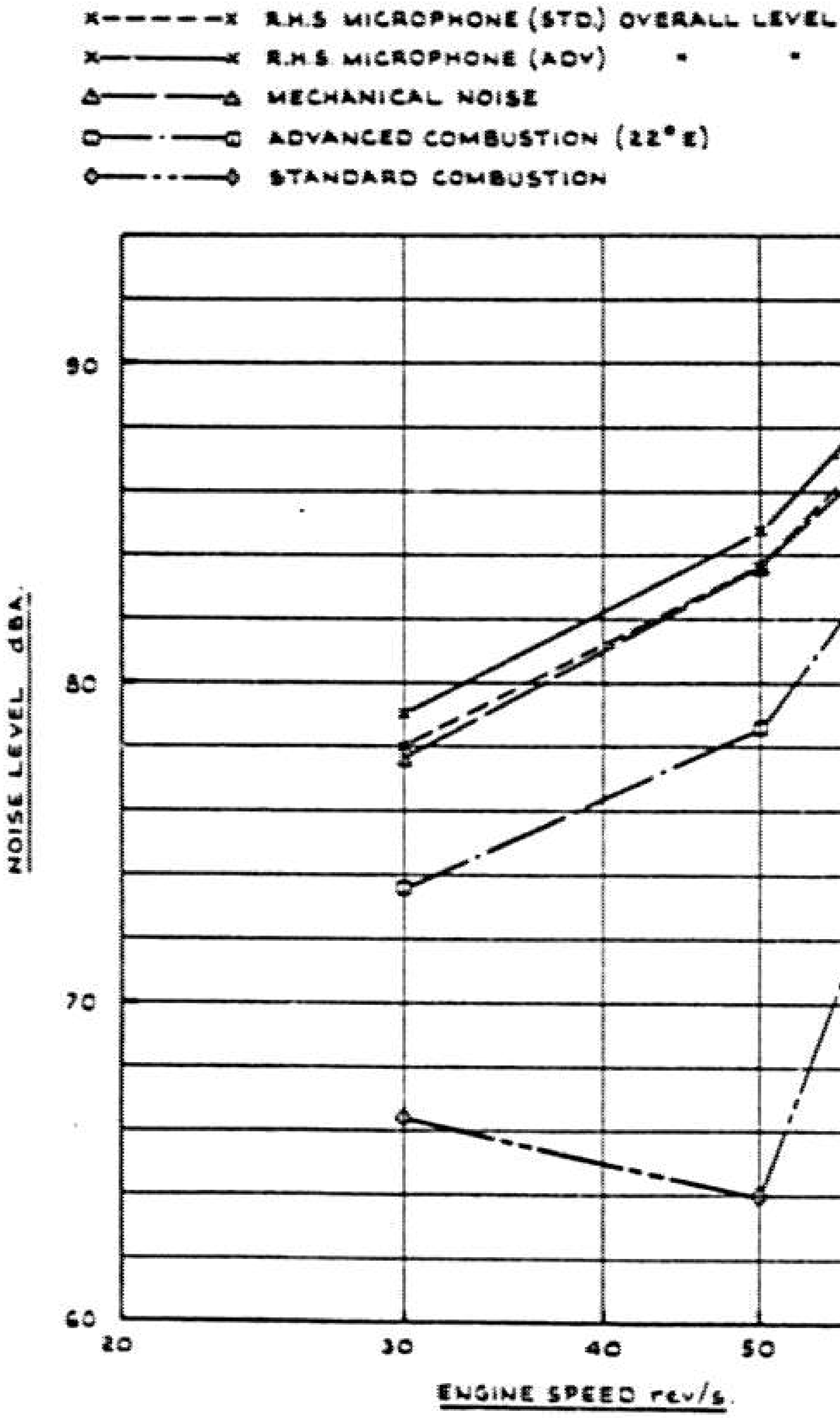


FIGURE 4-30. MECHANICAL/COMBUSTION NOISE BREAKDOWN MIC. 1 - R.H.S. 100% LOAD

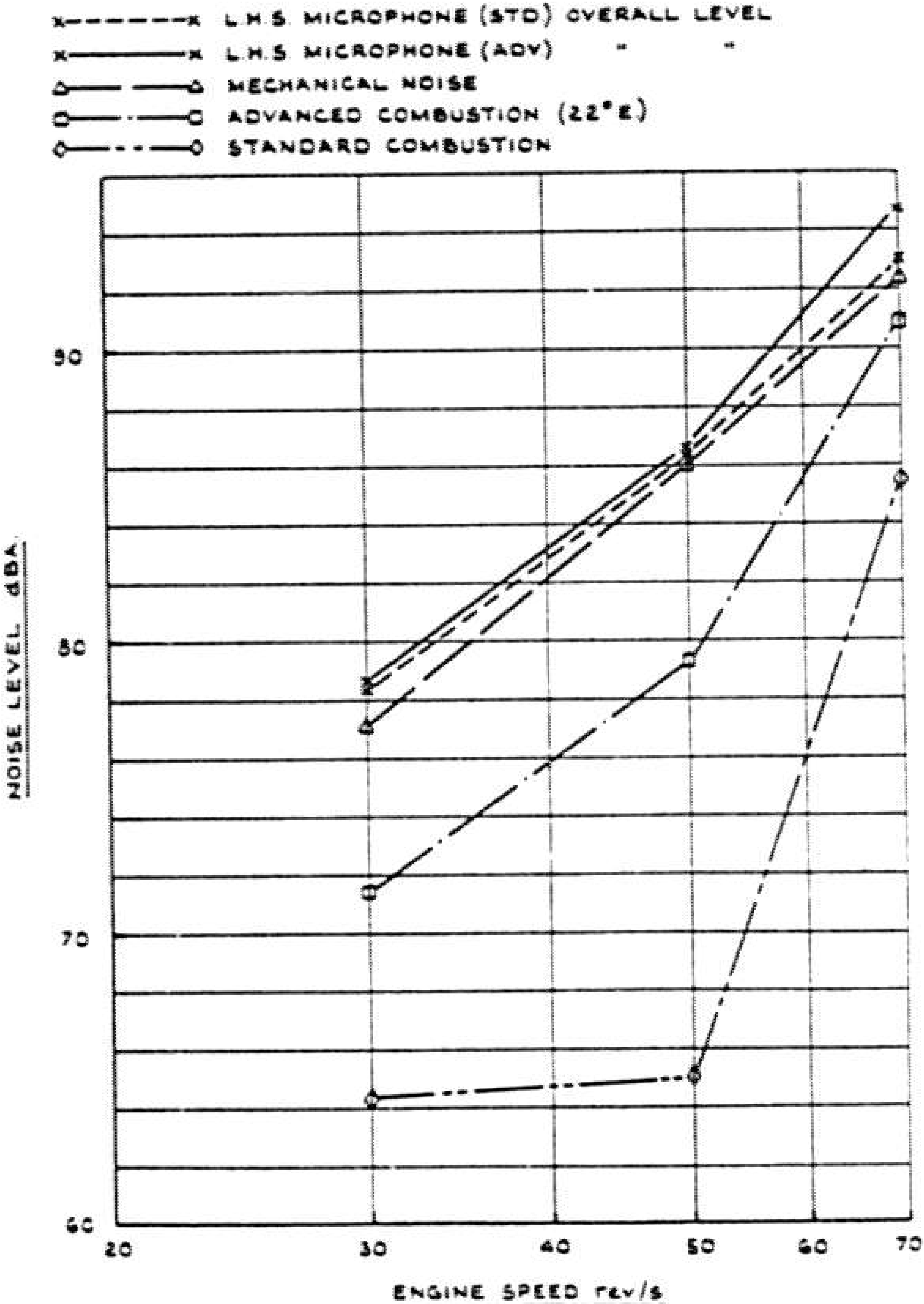


FIGURE 4-31. MECHANICAL/COMBUSTION NOISE BREAKDOWN. MIC. 2 - L.H.S. 100% LOAD

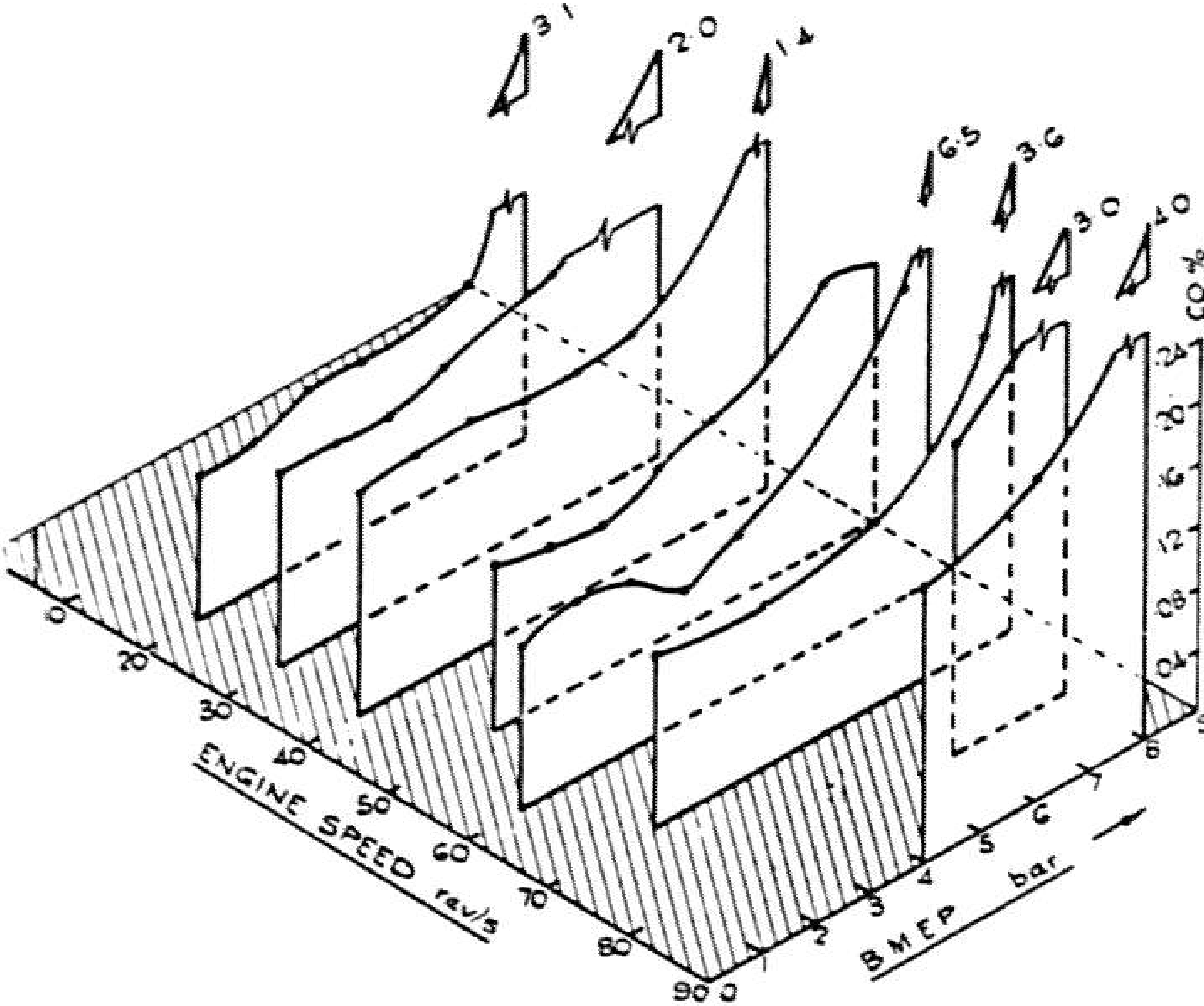


FIGURE 4-34. CO EXHAUST EMISSIONS OVER THE LOAD AND SPEED RANGE

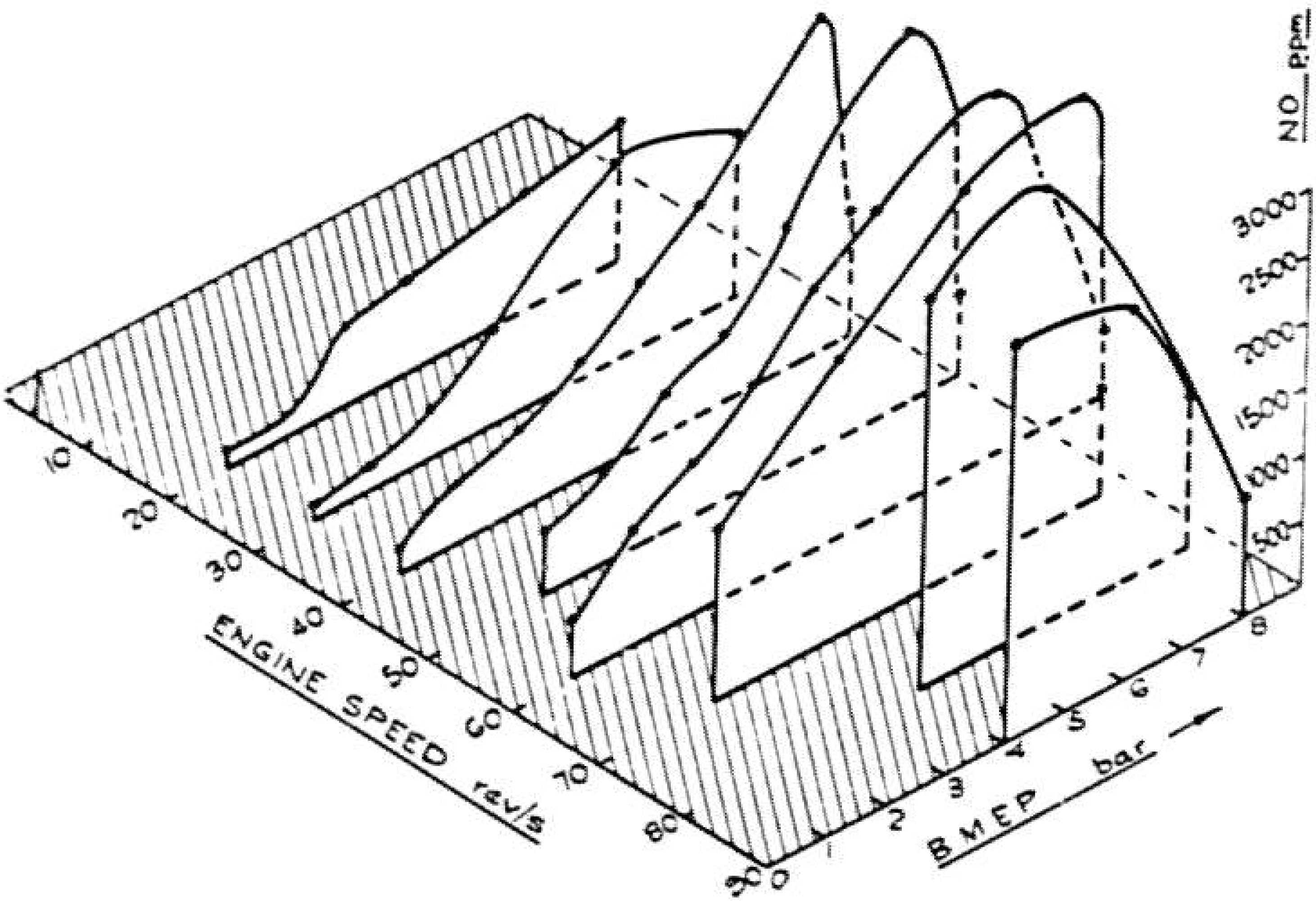


FIGURE 4-32. NO EXHAUST EMISSIONS OVER THE LOAD AND SPEED RANGE

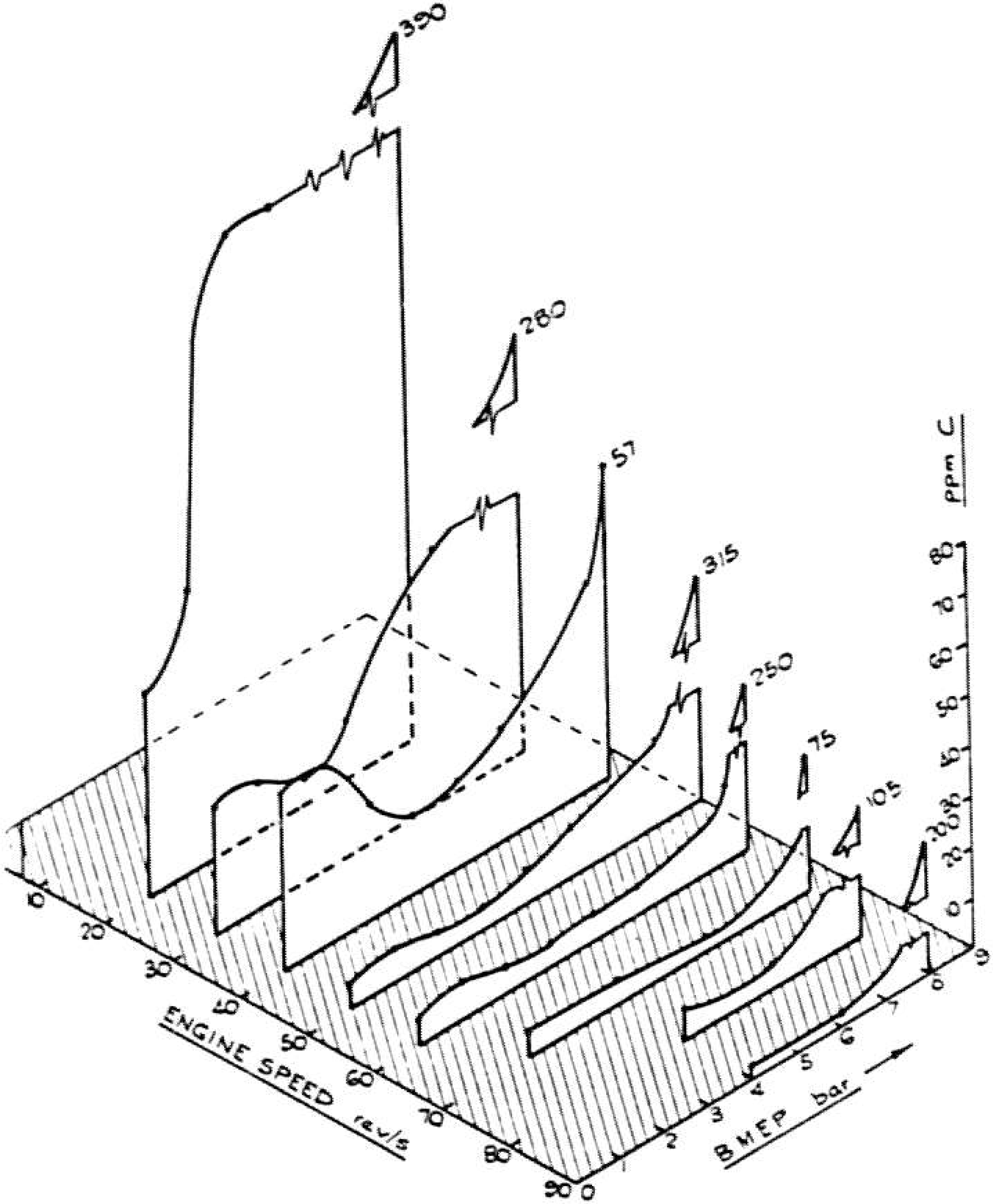


FIGURE 4-33. HC EXHAUST EMISSIONS OVER THE LOAD AND SPEED RANGE

5. TESTS ON A PEUGEOT 2.3-LITER DIESEL ENGINE

5.1 INTRODUCTION

This report covers test work carried out on a Peugeot 504 GL D 2.3 litre Comet V indirect injection engine (94ϕ x 83mm x 4 cyl), in the XD2 1976 Californian build. These tests formed part of a program of noise, performance, economy and emissions evaluation of two passenger cars and their respective engines, the cars in question being the Peugeot 504 GLD and the Saab 99 GL injection. The test work on these cars was initially reported in Ricardo report DP 77/1158. Report DP 79/820 covers work on the Saab engine, and report DP 79/685 covers work completed on ten additional European passenger cars. The engines were retained in their low emission builds for the tests performed in the anechoic test cells.

The engine tests concentrated on noise measurements, but engine performance, fuel economy and exhaust emissions were also assessed, both with the engine in standard build (as removed from the car) and with the injection timing both advanced and retarded from standard.

Unless otherwise stated, all sound pressure levels are quoted to a reference pressure of 20μPa.

5.2 TEST ENGINE

The engine tested was a Peugeot XD2 diesel engine (as installed in the Peugeot 504 GLD car) of 2.304 liter capacity, with four cylinders of bore and stroke of 94 x 83mm and in 1976 Californian build. The engine was installed and tested complete with the standard manual 4-speed gearbox, the drive being taken from the gearbox output. The gearbox was overfilled with oil to prevent overheating of the rear bearing and oil seal. A description of the test engine appears in Table 5-1.

5.3 TEST FACILITY

The engine was installed in Ricardo Anechoic test cell 'E' with the exhaust and intake piped outside the cell to roof-mounted Burgess ADS 6 silencers. Engine power was taken via a plummer shaft to a Schenck 230 dynamometer mounted outside the cell. Cell dimensions were approximately 4.5m x 4m x 4m high, with all internal surfaces lined with 100mm thick acoustic grade open cell polyurethane foam (Dunlop DF120). The cell was calibrated immediately prior to the engine tests being performed, details of this work appearing in Ricardo DP 79/311. The cell gave true free-field conditions down to frequencies of approximately 250Hz. Photographs of the installation appear in Figure 5-1.

A four-microphone array was used for all the engine tests. Microphones 1 and 2 were placed one on each side of the engine, level with and at one meter from the cylinder head gasket edge. Microphone 3 was placed in front of the engine, level with and one meter away from the crankshaft pulley. Microphone 4 was one meter above the center of the valve cover. A schematic view of this arrangement is shown in Figure 5-2 and specifications of the noise measurement and analysis equipment are given in Table 5-2.

5.4 TEST PROCEDURE

For these tests, a 'complete' speed range of 20, 30, 40, 50, 60, and 75 rev/s was used, with an abridged range comprising speeds of 20, 30, 50 and 75 rev/s. The engine was tested under various load conditions, increments in bmep of 1 bar being used for detailed mapping tests, with 2 bar increments used in other cases. Tests were performed in the following categories:

5.4.1 Performance

At conditions of full rack, for builds with standard, advanced and retarded timing, brake torque, fuel consumption, Bosch smoke levels, fuelling levels and engine operating temperatures were recorded over the complete speed range.

5.4.2 Fuel Consumption Mapping

For the standard build only, engine fuel consumption was measured over the complete speed range at load (bmep) increments of 1 bar, to enable mapping of fuel consumption.

5.4.3 Cylinder Pressure Observation

As well as obtaining photographs of cylinder pressure and needle lift diagrams for full and part load operation at various engine speeds, frequency spectra of the cylinder pressure were obtained for operation at full load over the abridged speed range for the three different timings. Further spectra were obtained at low load, low engine speed to enable observation of the engine under typical urban driving conditions.

5.4.4 Noise Measurements

The sound pressure level was measured for the standard build at each of the four microphone positions over the complete speed range, with the load varying from zero to full in 2-bar increments. Some additional tests were made at low engine speeds (20, 30 and 40 rev/s) and at various loads. 1/3rd octave frequency spectra as well as linear and dBA-weighted levels were obtained at each measurement point.

Noise measurements were also made at conditions of hot and cold idle.

Noise measurements were made with the engine in both the advanced (build 2) and retarded (build 3) conditions at full load over the abridged speed range. Levels only were obtained at the other speeds, again at full load. These tests were performed to provide data to enable calculation of the relative importance of combustion and mechnical noise sources, by the procedure described in Ricardo DP 76/832.

5.4.5 Exhaust Emissions

HC, CO and NO levels were measured over the complete speed and load ranges for the standard engine build, to enable complete mapping of emission levels. The levels were also measured over the complete speed range at full load only for the advanced and retarded engine builds. The instrumentation used during these tests was the standard Ricardo equipment, as is outlined in Table 5-3.

5.5 TEST RESULTS

5.5.1 Performance

Full-load performance and timing curves are shown in Figures 5-3 and 5-4, the results are all corrected to conditions of 20°C and 760mmHg barometric pressure, by the procedure described in DIN 70020.

Maximum bmep of 7.1 bar occurred at an engine speed of 30 rev/s. Maximum power of 47.5kW was produced at 75 rev/s.

The fuelling curve shows a peak at 30 rev/s of 34.4mm^3/injection. At higher engine speeds, fuelling increased gradually from 33mm^3/injection at 45 rev/s to 34.6mm^3/injection at rated speed. The fuelling level indicated at 50 rev/s appears to be low when compared with later build plots.

Bosch smoke levels were in the range 1 to 1.5 for engine speeds above 30 rev/s.

The brake fuel consumption was at a minimum of 270g/kWh at 20 rev/s, rising with engine speed to a maximum of 343g/kWh at rated speed.

The dynamic timing plot (Figure 5-4) shows that the pump gave only slight increase in timing advance with increase in engine speed, the start of needle lift timing varying from 10°D to 15°E over the speed range.

The performance of the advanced and retarded timing builds is also shown in Figure 5-3. Output bmep and power are slightly increased (typically by 2 1/2 percent) for the advanced build, and as fuelling levels are similar for the two builds, this results in slightly improved fuel consumption. Smoke levels for the advanced build were slightly higher than those of the standard over the speed range.

The torque and power curves for the retarded build show a typical deterioration in performance of approximately 4 percent compared to the standard build. Fuelling levels were very slightly higher than those of the standard and advanced builds, and fuel consumption was 4 1/2 to 6 percent greater than that of the standard build over the speed range. At an engine speed of 30 rev/s there was a flattening of the torque curve (when compared with the shape of the curve for the other builds), this corresponding to the peak in the fuelling curve common to all engine builds. Smoke levels further illustrated this trend, levels being generally lower than for the standard build over the speed range, but at 30 rev/s the level was significantly higher (Bosch level 3.2).

The timing plots (Figure 5-4) shows that over the speed range (at full load) the Start of Needle Lift (SNL) timing was approximately 1 1/2 to 2° cr advanced over the standard for build 2, and approximately 4° cr retarded from standard for build 3. End of needle lift timing followed similar trends. The timing of the start of combustion was difficult to determine at low engine speeds and for the retarded build as the cylinder pressure diagram under these conditions was very smooth and showed no clear pressure rise due to combustion.

5.5.2 Fuel Consumption

A 3-D plot showing the variation in fuel consumption with changes in speed and load appears in Figure 5-5. At all engine speeds, consumption decreased with increase in load up to the maximum. At low loads, the BSFC varied between 560 g/kWh at 20 rev/s to 820 g/kWh at 75 rev/s.

(Fuel consumption at full load only for the advanced and retarded builds may be compared with the standard engine by reference to the full load performance curves in Figure 5-3).

5.5.3 Cylinder Pressure

Plots of the cylinder pressure frequency spectra are shown in Figures 5-6, 5-7 and 5-8. These show the effect of load and speed on the standand engine build.

Figures 5-9 and 5-10 show the effect of speed at the advanced and retarded conditions, and Figures 5-11 and 5-12 show the effects of timing change at full load at engine speeds of 20 and 75 rev/s.

Differences between the levels obtained for the different builds were slight, and as a direct result of this results of the combustion/mechanical breakdown were unreliable except for operation at 30 rev/s. Results for the calculations at this speed are shown in table form in Figures 5-13 and 5-14.

5.5.4 Noise Tests

Results for the standard build noise tests are shown in Figure 5-15. They indicate a maximum noise level of approximately 101dBA at rated speed operation. At high speeds, the noise is not load-dependent, whereas at low engine speeds there is a significant increase in noise level with load, typically 3-4 dBA difference in level between no and full load operation at 20 rev/s.

Within repeatability limits, the 2 and 4 bar load results confirm the load dependence.

Results for the hot and cold idle tests were as follows (idle speed 13 rev/s):

	Mic 1 dBA	Mic 2 dBA	Mic 3 dBA	Mic 4 dBA	Log Ave dBA
Hot idle	74.0	75.6	77.2	72.6	75.2
Cold idle	76.8	78.2	81.6	77.8	79.0

Figure 5-16 shows the effect of timing on the full noise levels. At low engine speeds, levels for the retarded build were slightly lower than those for the standard, typically by 1 to 1 1/2 dBA. At higher speeds, the levels were the same, within repeatability limits.

Levels for the advanced condition were higher than those of the standard and retarded builds, the increase above retarded levels being typically 1 1/2 dBA at low speed increasing to approximately 3 1/2 dBA at rated speed.

Frequency spectra illustrating the effects of speed and load changes on standard build noise appear in Figures 5-26 to 5-37.

Idle noise frequency spectra are shown in Figure 5-38.

The effects of timing changes on the noise frequency spectra are shown in Figures 5-39 to 5-42.

5.5.5 Exhaust Emissions

Figures 5-17-5-19 show the effects of load and speed changes on the HC, CO and NO emission levels of the standard build engine.

The hydrocarbons show high HC emissions levels at low load, decreasing with increase in load. The HC levels show only a slight variation with change in engine speed, except that for an engine speed of 30 rev/s, levels measured were consistently higher than found at other speeds. The levels for 20, 30 and 40 rev/s operation were checked to eliminate the possibility of equipment malfunction. At a typical condition of 40 rev/s, 4 bar operation, the HC level was 52 ppmC. No-load levels were in the range 160 to 250 ppmC.

CO emissions showed both speed and load dependence. At low loads, increase in engine speed resulted in an increase in the CO level from 0.4 percent to 0.7 percent, whereas under full load conditions increase in engine speed caused an initial decrease in the level to a minimum at 50 rev/s, further increase in speed causing a slight increase in the CO level. At all engine speeds, increase in load caused an initial decrease in the CO level to a minimum at approximately 75 percent full rack load, followed by increased levels to a maximum full load. A typical minimum level reached (e.g. for 40 rev/s, 4 bar) was 0.015 percent. A maximum level of 0.072 percent was produced at 75 rev/s, no load operation.

The NO emissions (as expected) tend to show trends reversed from those of the CO levels. Minimum levels were obtained under low and no load conditions, rising to maxima at approximately 90 percent full load. Full rack operation resulted in slight decreases in the NO level from these maxima. No load levels were in the range 20 to 60 ppm (rising with increase in speed), and maximum levels were typically approximately 250 ppm.

Figure 5-20 shows the effects of speed and load changes on the Bosch smoke levels of the exhaust of the standard engine.

Figure 5-21 shows the effect on the full load emissions levels of changes in the dynamic timing.

Little significant difference exists between the standard and advanced build results for HC and CO emissions, marginally higher levels being shown for the advanced build. However, a marked increase in NO levels for the advanced build is evident at high engine speeds. At rated speed, full load, timing advance caused a NO level increase from 250 to 420 ppm.

The retarded build resulted in very high HC and CO levels at an engine speed of 30 rev/s. (As the levels were very high at this one point only, several check tests were performed which confirmed the results' validity). At all other speeds levels were (within repeatability limits) the same as for the standard build. The NO levels were the same as for the standard build over the whole of the speed range.

5.6 DISCUSSION

5.6.1 Performance and Fuel Consumption

The peak torque measured of 130 Nm @ 30 rev/s (corresponding to 7.1 bar bmep) agrees well with the manufacturer's specified figure of 131 Nm @ 33 rev/s. Maximum power measured was approximately 8 1/2 percent lower than the specified figure of 52.2 kW at rated speed. The difference is most probably due to the difference in testing arrangements - the engine was tested with the gearbox fitted, and the gearbox deliberately overfilled to prevent over-heating of the rear bearing. Power losses of this order are thus to be expected, especially at high speeds due to churning of the gearbox oil.

The shapes of the curves and the levels measured for engine output and fuel consumption, smoke etc. were typical for this type of light duty Comet V engine, allowances being made for the likely losses in the power train. Dynamic timing values were also typical for an engine of this type, optimized for performance and economy rather than low noise.

Fuel consumption over the load and speed ranges was as expected for this type of engine - at very light loads specific fuel consumption was high, increase in load causing specific consumption decrease. Minimum fuel was used under low speed, mid to high load conditions.

Performance results for the advanced timing build were generally as expected, the 2° crank timing advancement resulted in slight increases in output torque at the expense of a small increase in Bosch smoke level. Fuel consumption was improved by approximately the same factor as the output power increases (approximately 2 1/2 percent). As a general rule, advancement of the timing would be expected to cause a slight decrease in exhaust temperature, but for this engine the advanced timing build resulted in exhaust temperatures slightly higher than those of the standard.

Check tests were run on the standard build results, which were shown to be repeatable.

Performance of the retarded build was again as expected, except for operation at 30 rev/s. Over the rest of the speed range, the brake torque was lower than the standard and the fuel consumption greater, with some improvement in the smoke levels. Exhaust temperatures were higher than those of the standard or advanced builds over the whole of the speed range.

For 30 rev/s operation, the retarded build showed very poor performance, with a flattening of the torque curve and high peaks in the smoke and fuel consumption plots.

A possible explanation for these results is that at this particular speed, there was simply insufficient time for total combustion when running with retarded timing. There is a peak in the fuelling curve at this speed. At engine speeds slightly below and slightly above 30 rev/s, fuelling levels were considerably lower (approximately 4 percent, so reducing the likelihood of combustion being incomplete before the start of exhaust. The exhaust emission results (discussed later) show high peaks in the CO and HC levels at this running condition, as would be expected if fuel was remaining unburnt.

5.6.2 Noise Tests

The maximum noise produced by the standard build engine was approximately 101dBA, which agrees well with the Ricardo prediction based on the engine type, bore diameter and rated speed, the predicted level being 101dBA ± 2dBA. The formula used for this prediction is:

$$dBA = 43 \log_{10} N + 60 \log_{10} B - 98$$

(N in rev/s, B in mm, dBA at 1m).

The effects of speed and load changes on the overall A-weighted noise levels for the standard build were typical for this engine type. Full load results show a gradual change in slope of the noise v engine speed plots with increase in speed, the slope changing from approximately 20dB/decade at low engine speeds to 50 dB/decade at rated speed. This variation in slope is due to changes in the relative importance of the combustion and mechanical noise sources. Consideration of the cylinder pressure and noise frequency spectra (Figures 5-7, 5-8 and Figures 5-31 and 5-35) for operation at 20 and 75 rev/s serves to illustrate the variation in dependence of the overall noise on these different sources.

At high engine speeds, the cylinder pressure levels at frequencies below 1kHz were greater for no load operation than for full load operation. Above 1kHz, levels for full load operation were higher (see Figure 5-8). These trends are not reflected in the noise frequency spectra (Figure 5-35) so implying that at high engine speeds and combustion noise was not the controlling factor in the overall radiated noise. The very small load dependence of the rated speed noise thus suggests that for the standard build at high engine speed, mechanical sources controlled the radiated noise.

At low engine speeds the radiated noise showed a considerable load dependence (approximately 3dBA @ 20 rev/s). The cylinder pressure spectra for low speed operation (Figure 5-7) shows that, over the frequency range of interest (approximately 400Hz to 8kHz) the cylinder pressure levels for full load operation were greater than those for no load operation, with the greatest differences in the range 800Hz to 2kHz frequency range. This is most noticeable in the results obtained for the left hand side of the engine (see Figure 5-31). Thus it may be concluded that combustion noise was a significant source at low engine speeds. Piston slap may also be a significant source under these conditions. Factors affecting the magnitude of the noise generated by piston slap include the cylinder pressure effective when the piston slap occurs (i.e. approximately T.D.C.), the piston to cylinder clearance, and the geometry and design of the piston, connecting rod and crankshaft.

Results of the tests run at low engine speeds and with different timings (discussed in more detail below) indicate that for this engine the maximum cylinder pressure was load dependent. (Photographs of the cylinder pressure diagram for no load operation are not available). The cylinder pressure diagram for the standard build at 20 rev/s full load (Figure 5-22), shows a pressure increase due to combustion, most clearly recognized by comparison with the similar diagram for the retarded build (Figure 5-25) for which the pressure increase is much reduced. Thus it may be concluded that, for the standard build, the maximum cylinder pressure is determined by pressure increase due to combustion above the maximum compression pressure, and therefore the no-load maximum cylinder pressure will be less than the full load value. Thus piston slap, which is in part dependent on the maximum cylinder pressure, is likely to be greater for full load operation than no loal. (This effect may be off set to a greater or lesser degree by piston temperature changes, which may reduce the bore clearances and thus the piston slap at full load). The overall pattern thus appears to be that at low engine speeds the radiated noise is controlled by piston slap and combustion noise sources, whereas at higher engine speeds other mechanical noise sources are dominant.

The effect of timing on the full load noise was as expected, except that little reduction in noise was achieved with the retarded condition (reasons for this are discussed below). For the timing advanced build, noise levels were increased over the complete speed range, with a greater increase at rated speed than at rated speed than at low engine speeds. The noise increase occured over the complete frequency range as may be seen from the spectra (Figures 5-41 and 5-42). The effect was most pronounced on the right hand side of the engine. The retarded timing build resulted in only slightly lowered levels over the whole of the speed range. (Typically, 1 1/2 dBA at 20 rev/s reducing to 1/2 dBA at 75 rev/s). At low engine speeds, where combustion noise and piston slap appear to be the major noise sources for the standard build, the retardation of timing has caused a drop in the maximum cylinder pressure of approximately 8 bar (120 psi (see Figures 5-22 and 5-25), whereas the advanced timing build caused an increase of only approximately 2 1/2 bar (40 psi) (Figure 5-24). The cylinder pressure diagrams for these builds (Figure 5-11) show that although the advanced build resulted in higher levels in the 100 to 400 Hz frequency range, levels in the important 400 Hz to 8 kHz range were similar to those of the standard build. Over the same frequency range, the retarded timing build shows some reduction in level compared with standard. These factors all suggest that, at low engine speeds at least, the advanced timing has little effect on piston slap (as P_{max} was not significantly altered) or combustion noise. This would appear to explain why, at low speeds, radiated noise levels for the standard and the advanced timing builds were similar.

In contrast, retarding of the timing appears to have caused reductions in both the piston slap (due to the lowering of P_{max}) and the combustion noise. As these were the controlling factors in the radiated noise of the standard build engine, overall noise levels for the retarded timing build at low speed were lower than those obtained with the standard timing.

At high engine speeds, the effects of timing change were different. Inspection of the cylinder pressure diagrams and frequency spectra (Figures 5-24, 5-25 and 5-12) shows that the retarded timing build caused only slight decreases in P_{max} and cylinder pressure levels at the frequencies of interest. Also, for high engine speed operation, combustion noise and piston slap appear to be less significant than other sources in the overall radiated noise of the standard engine (as described earlier). Reduction of these sources by timing retard thus caused little reduction in the overall radiated noise.

For the advanced timing build, however, the cylinder pressure diagram for rated speed operation (Figure 5-24) shows that, although P_{max} was not significantly higher than for the standard engine, there was a plateau of considerable duration (approximately 15° cr) at the maximum cylinder pressure compared with the short duration peak of the other builds. The cylinder pressure frequency spectra show the advanced build to have caused increases in the levels at frequencies of 1 kHz and above, and the noise frequency spectra (Figure 5-42) show the increases in level over the standard build results to have occurred at these same higher frequencies (greater than 1 kHz). These results imply, that, for the advanced timing build, the combustion noise was considerably higher than for the standard timing, and was in fact now a significant contributor to the overall noise radiated.

One factor which is worthy of comment is that, although the start of needle lift timing for this engine is typical for a performance optimized Comet, the initial rate of injection is rather low, as may be seen from the needle lift traces (Figures 5-22 to 5-25). This results in a somewhat retarded timing for the start of combustion and probably accounts for why the noise levels did not respond significantly to timing retard; the standard timings were effectively close to optimum from noise considerations.

Idle noise levels and their response to temperature for this engine were typical for the engine type, the average level to the sides of the engine being 74.9 dBA. Cold idle levels were approximately 2 1/2 to 3 dBA higher than hot idle results, probably due primarily to increased piston clearances (and thus piston slap) with the engine cold.

5.6.3 Exhaust Emissions

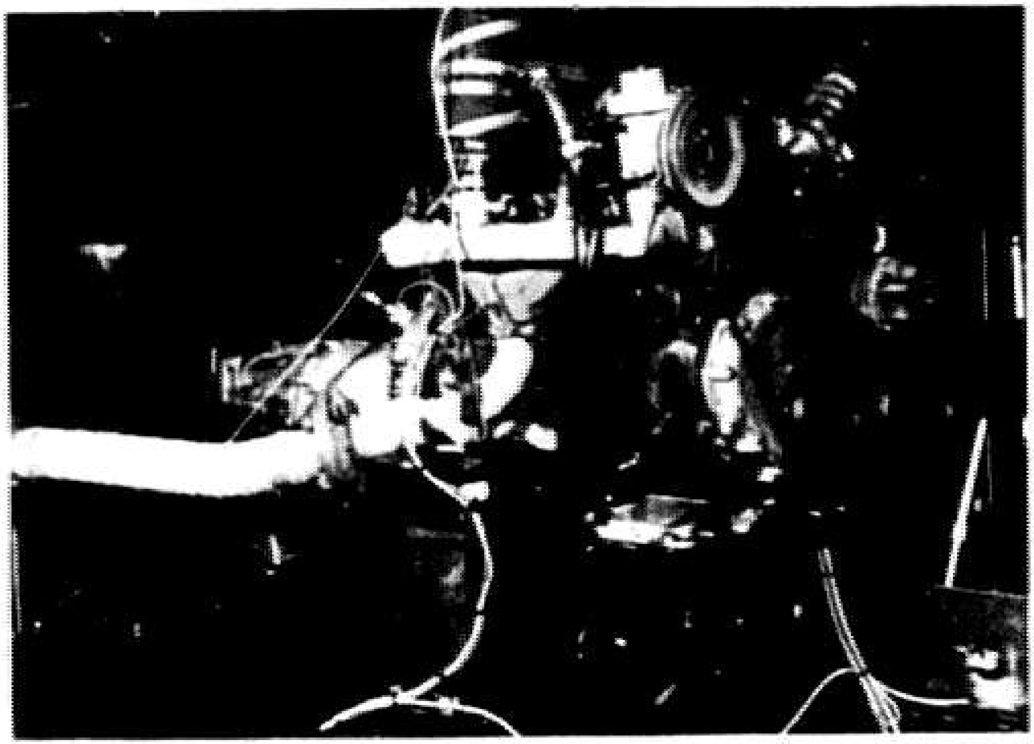
In general, the trends and levels shown during these tests for HC, CO and NO levels over the speed and load ranges were exactly as expected for a Comet V engine. The peak in the hydrocarbon plots at no load are most likely due to the slightly retarded start of combustion for the engine, and resultant combustion inefficiency. The consistently high levels at 30 rev/s were not typical, but are probably due to some anomaly in the fuel injection equipment such as a slightly secondary injection. (Figure 5-22 showing the needle lift trace for 30 rev/s, full load, does in fact show a very slight secondary injection at approximately 33° cr ATDC, and this secondary does not appear at any of the other speeds).

Carbon Monoxide levels were again typical of this engine type although possibly slightly lower than may normally be expected. The shape of the curves - an initial peak falling to a minimum level and then rising again with load increase, is most likely due to two different effects. At low loads, combustion temperatures are low and the flame has a tendency to quench before the charge is totally burnt. At high loads, with increased fuelling levels, it is likely that some fuel is still unburnt or partially burnt when the exhaust is opened, due to the higher fuel/air ratio.

NO emissions were also as expected, increase in speed and load causing increased charge temperatures and thus increased NO production. At full load, the effects of higher fuel/air ratios and the inefficient combustion as mentioned above cause reductions in the gas temperatures and thus slightly reduce the NO level. The NO levels were marginally lower than may have been predicted, due primarily to the (effectively) retarded start of combustion timing and resultant low gas temperatures.

Smoke levels were low for this engine, (1 - 1 1/2 Bosch). Levels of up to 50 percent higher may be normally expected with engines of this type. At full load over the speed range, typical Comet V smoke levels are usually around Bosch 2 and occasionally up to 3 to 3 1/2.

The effect of timing on the exhaust emissions was again fairly typical for the engine type, with the exception of the very high CO and HC levels measured at low speeds for the retarded build. These high levels were due to incomplete charge combustion at this particular running condition, as mentioned earlier in the performance discussion.



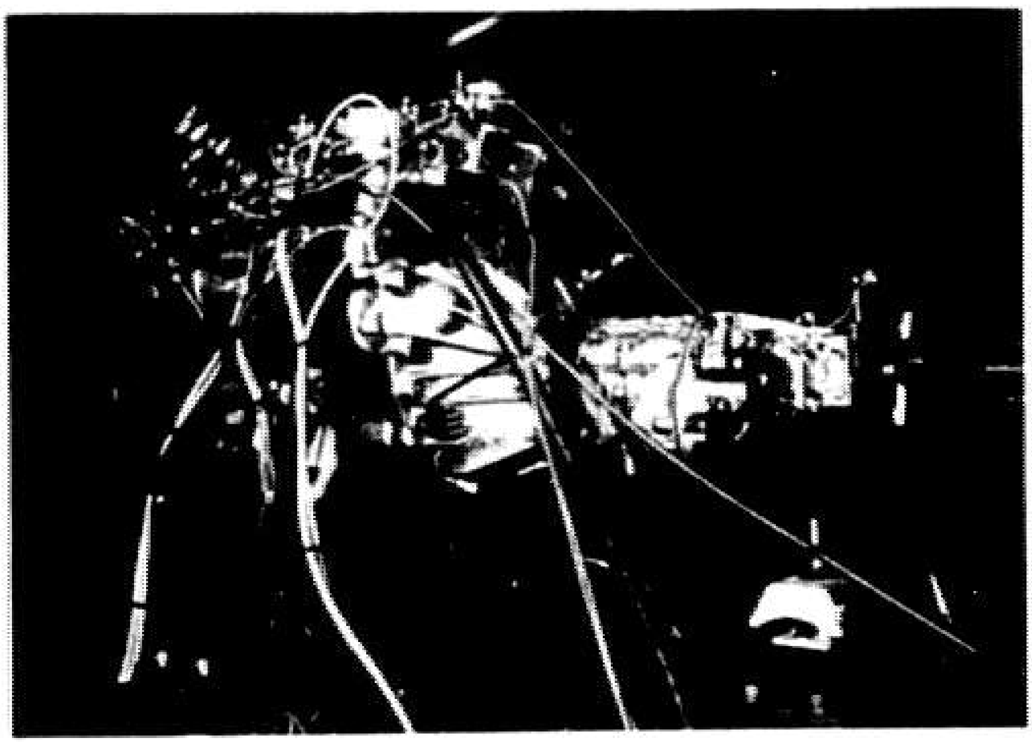


FIGURE 5-1. PEUGEOT XD2 GENERAL VIEWS OF INSTALLATION 94ϕ x 83 x 4 CYL. 2.3ℓ COMET V (ALL SUBSEQUENT FIGURES ARE BASED UPON THESE ENGINE SPECIFICATIONS)

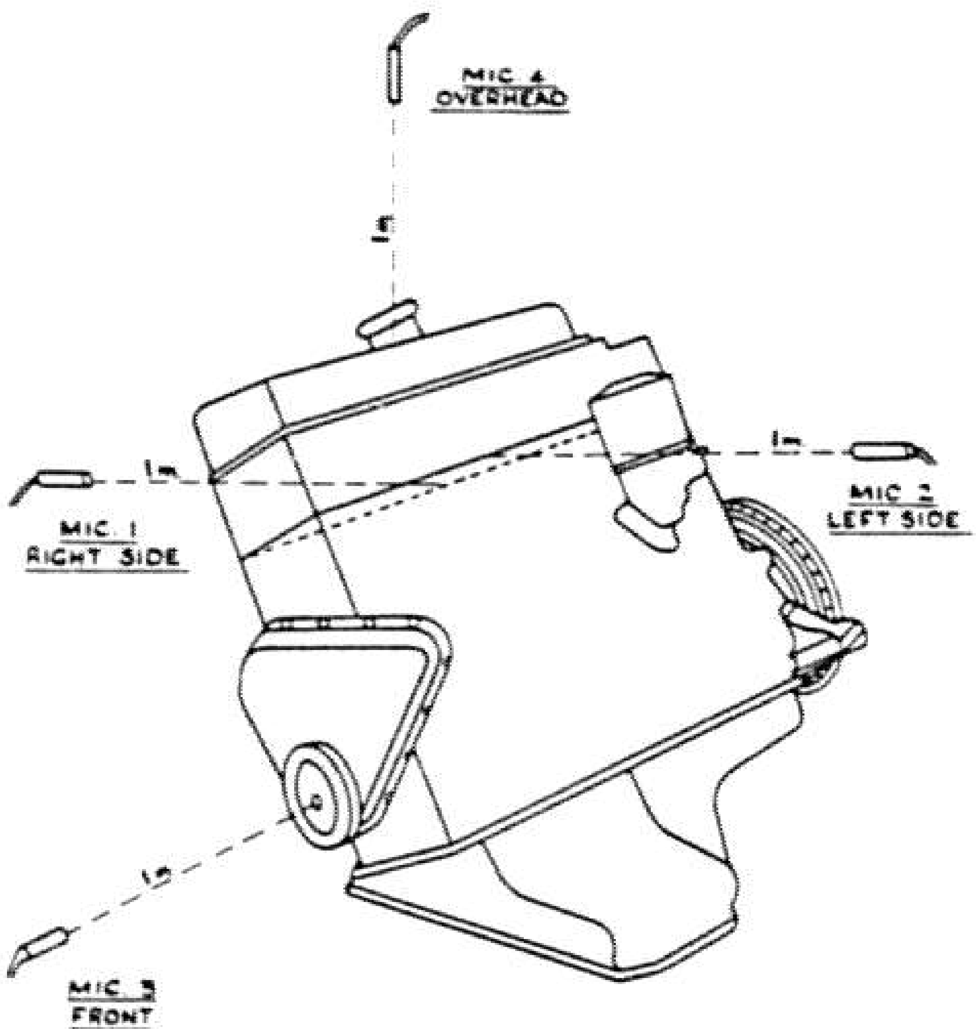


FIGURE 5-2. PEUGEOT XD2 MICROPHONE ARRANGEMENT-SCHEMATIC

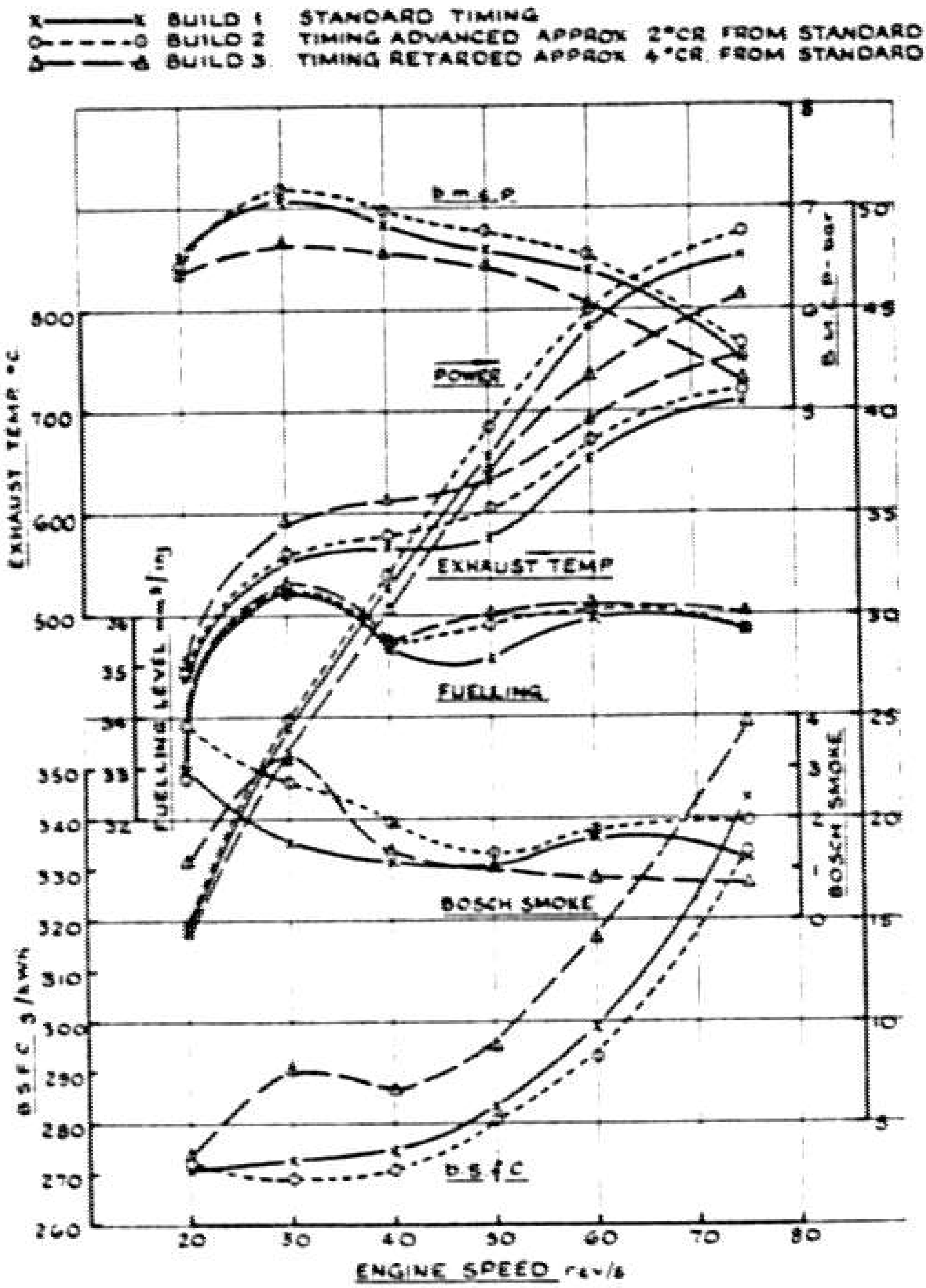


FIGURE 5-3. PEUGOT XD2 FULL LOAD PERFORMANCE CURVES

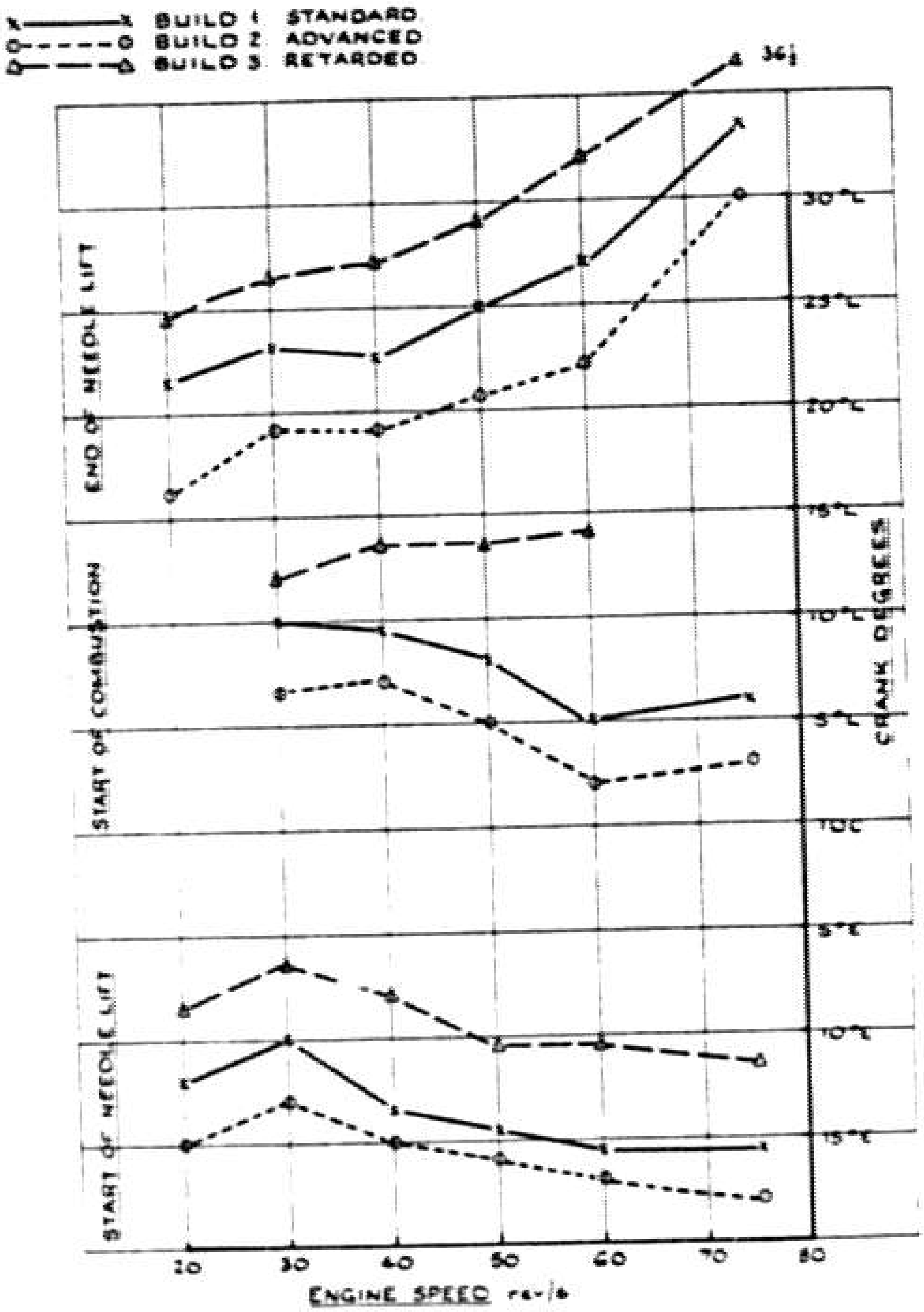


FIGURE 5-4. PEUGEOT XD2 DYNAMIC TIMING AT FULL LOAD

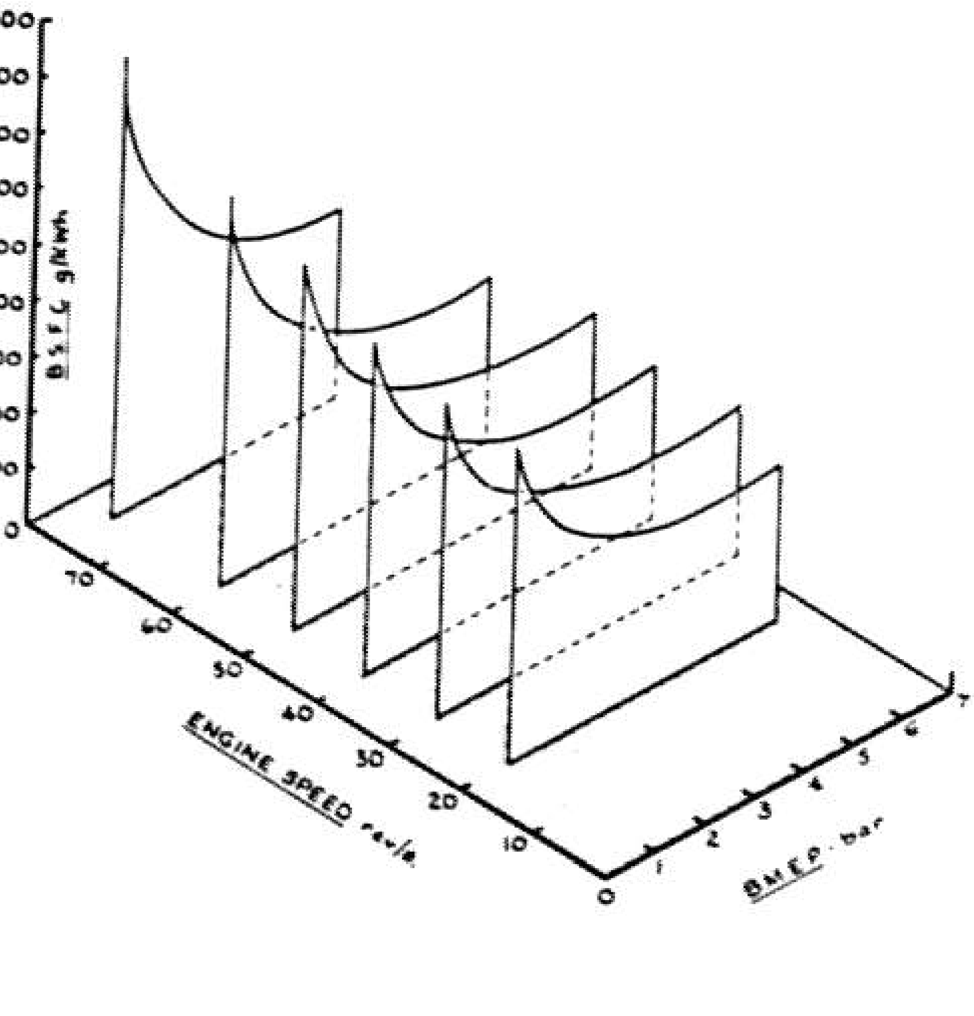


FIGURE 5-5. PEUGEOT XD2 FUEL CONSUMPTION OVER THE LOAD AND SPEED RANGES - BUILD 1

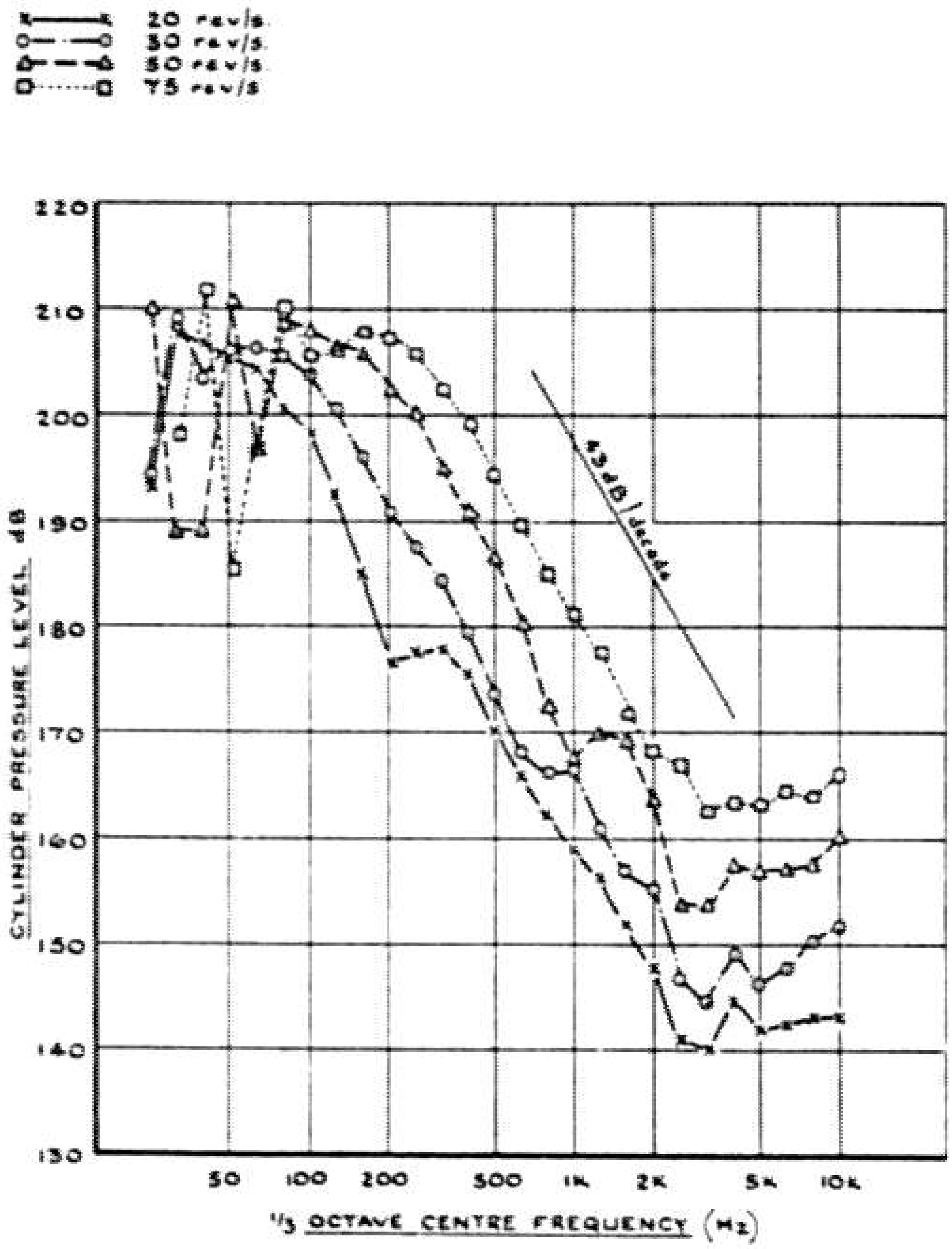


FIGURE 5-6. PEUGEOT XD2 EFFECT OF SPEED ON CYLINDER PRESSURE SPECTRA FULL LOAD. STANDARD TIMING

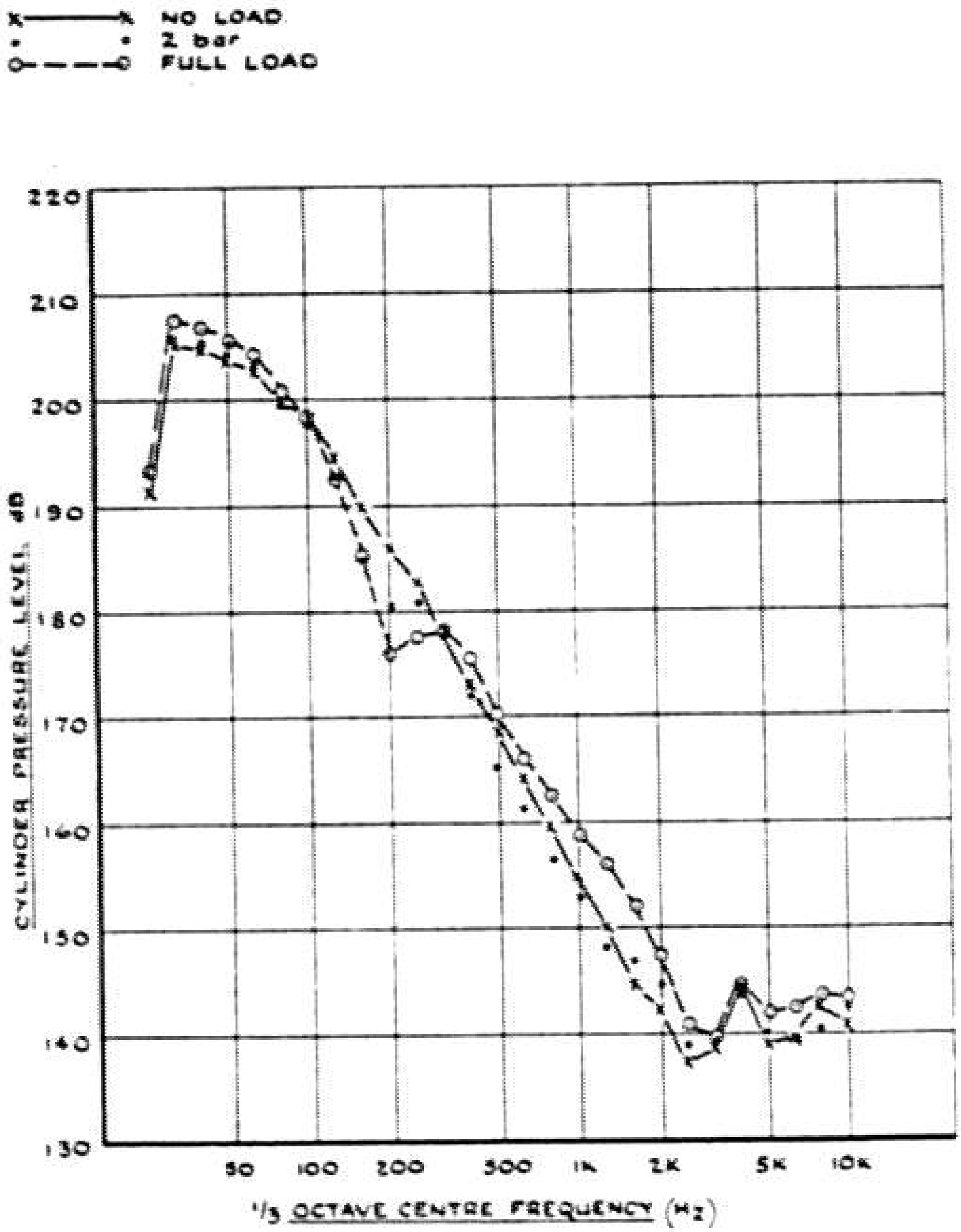


FIGURE 5-7. PEUGEOT XD2 EFFECT OF LOAD ON CYLINDER PRESSURE SPECTRA STANDARD BUILD 20 REV/S

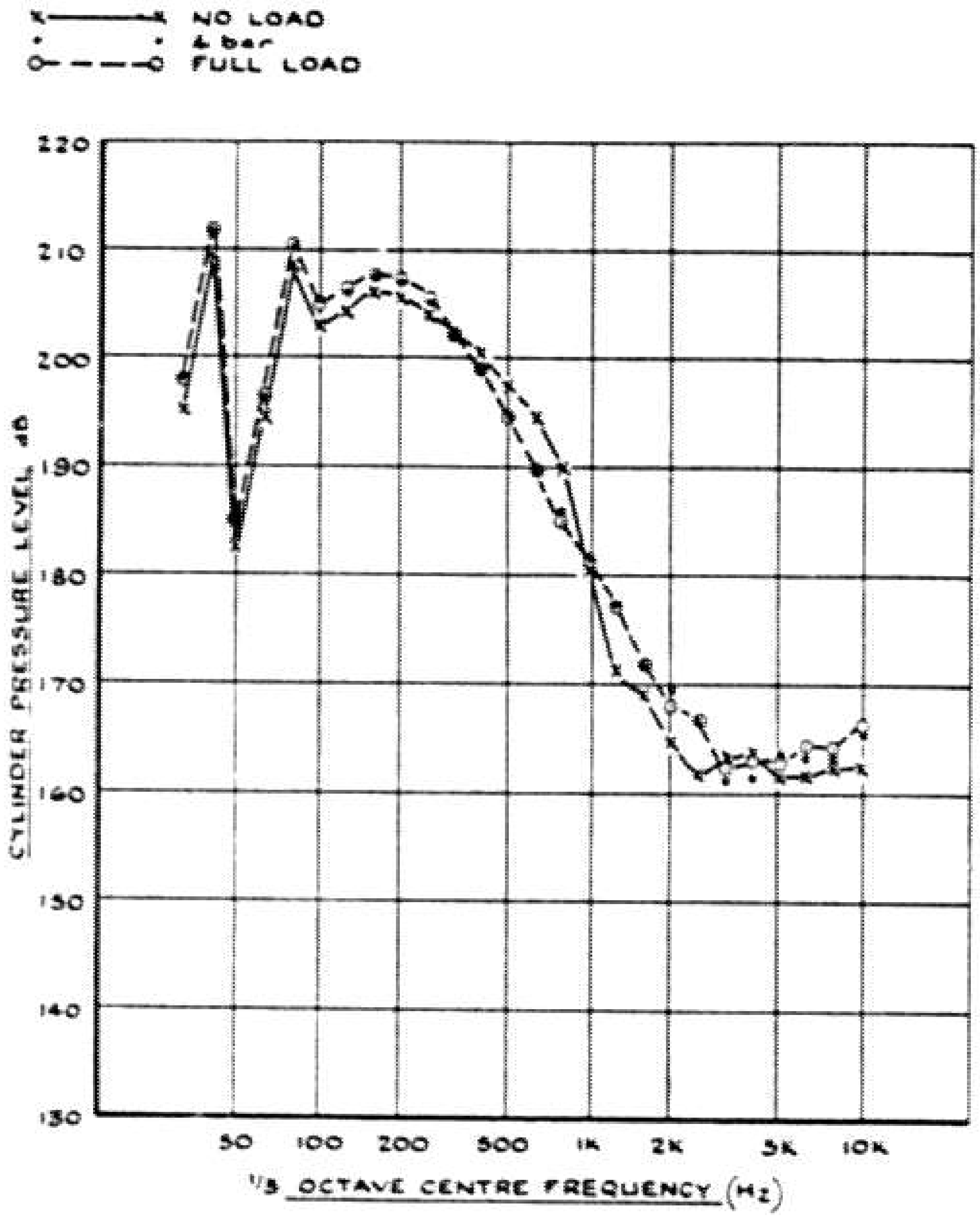


FIGURE 5-8. PEUGEOT XD2 EFFECT OF LOAD ON CYLINDER PRESSURE SPECTRA STANDARD BUILD 75 REV/S

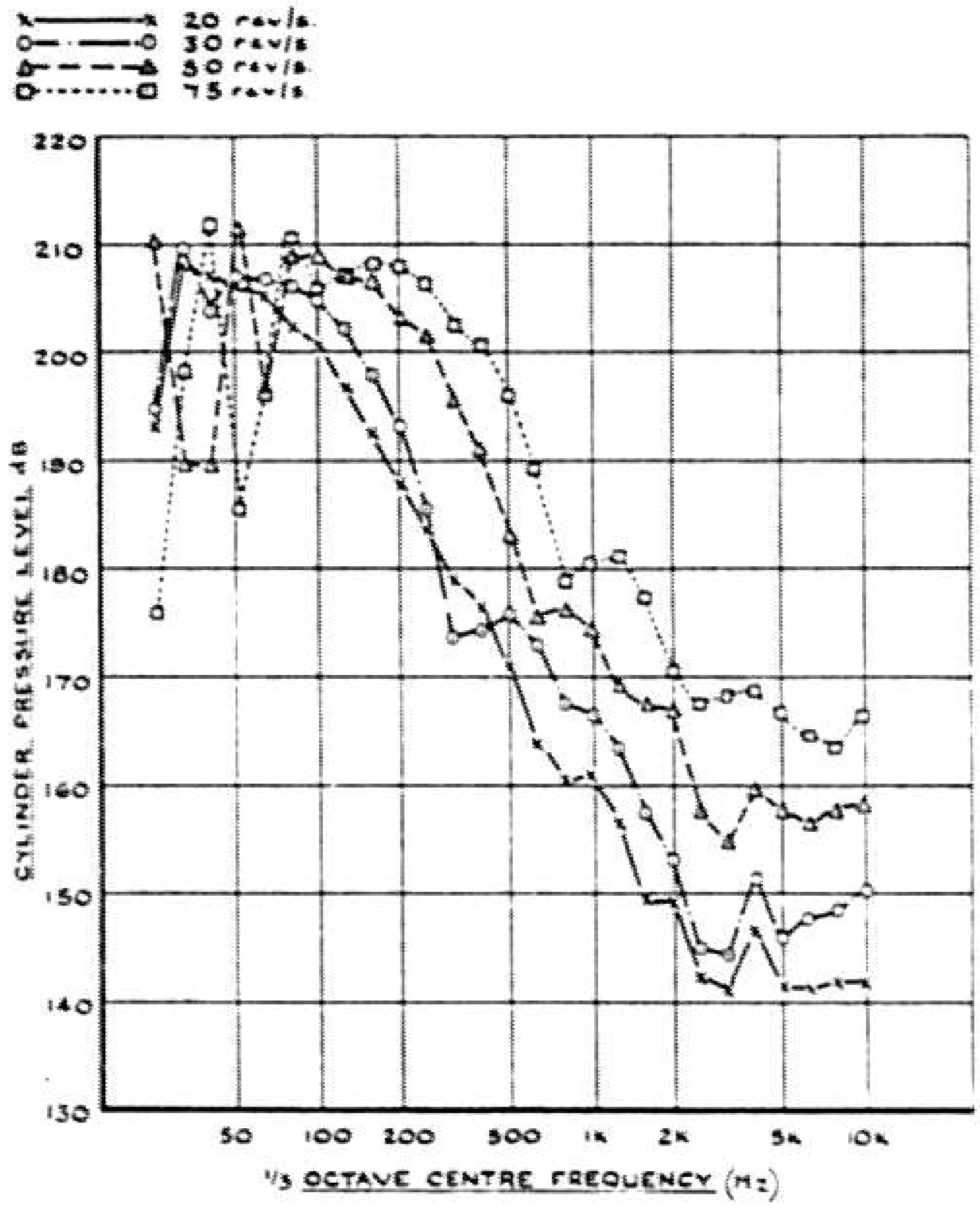


FIGURE 5-9. PEUGEOT XD2 EFFECT OF SPEED ON CYLINDER PRESSURE SPECTRA FULL LOAD, ABRIDGED SPEED RANGE ADVANCED CONDITION - BUILD 2

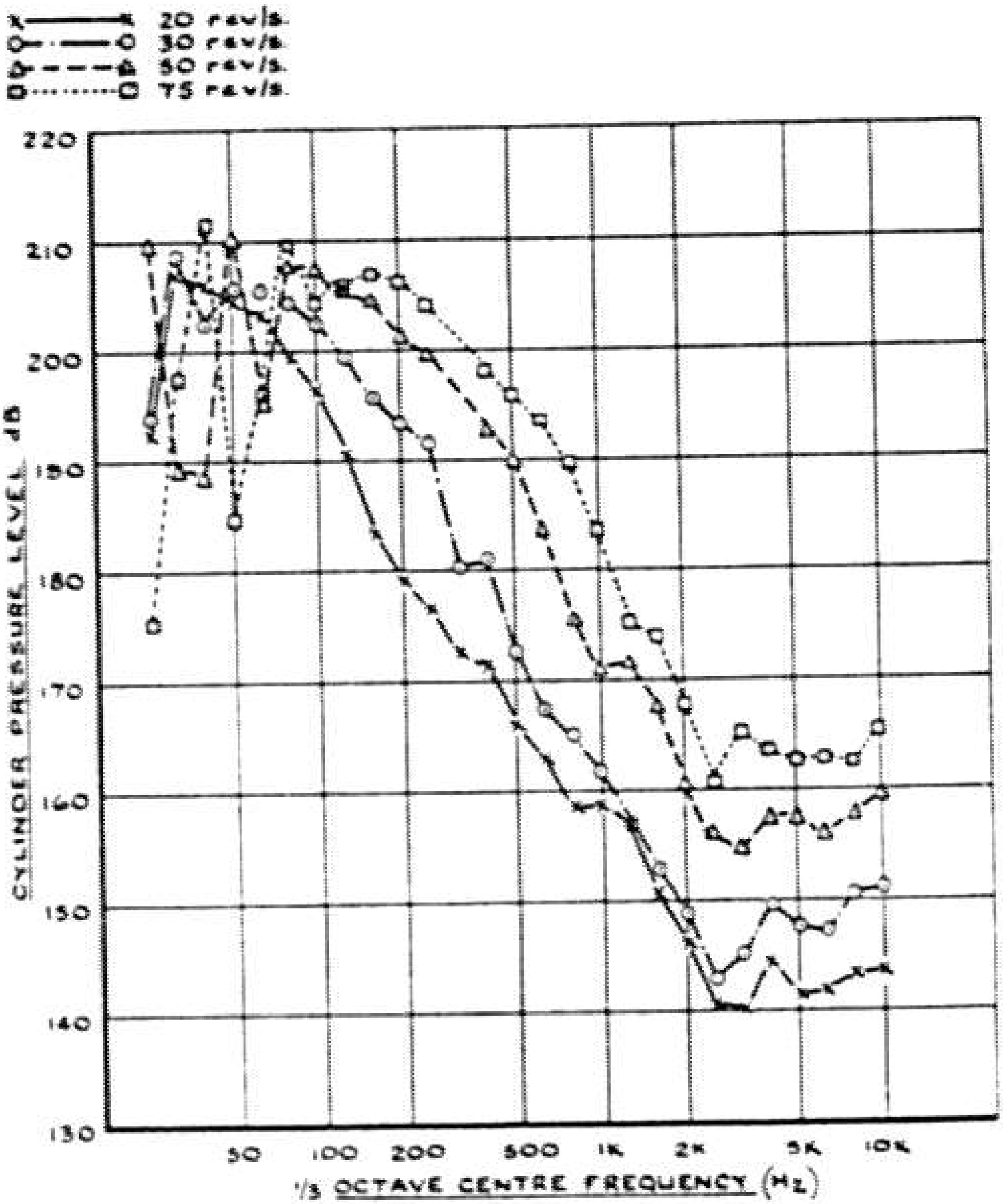


FIGURE 5-10. PEUGEOT XD2 EFFECT OF SPEED ON CYLINDER PRESSURE SPECTRA FULL LOAD, ABRIDGED SPEED RANGE. RETARDED CONDITION - BUILD 3

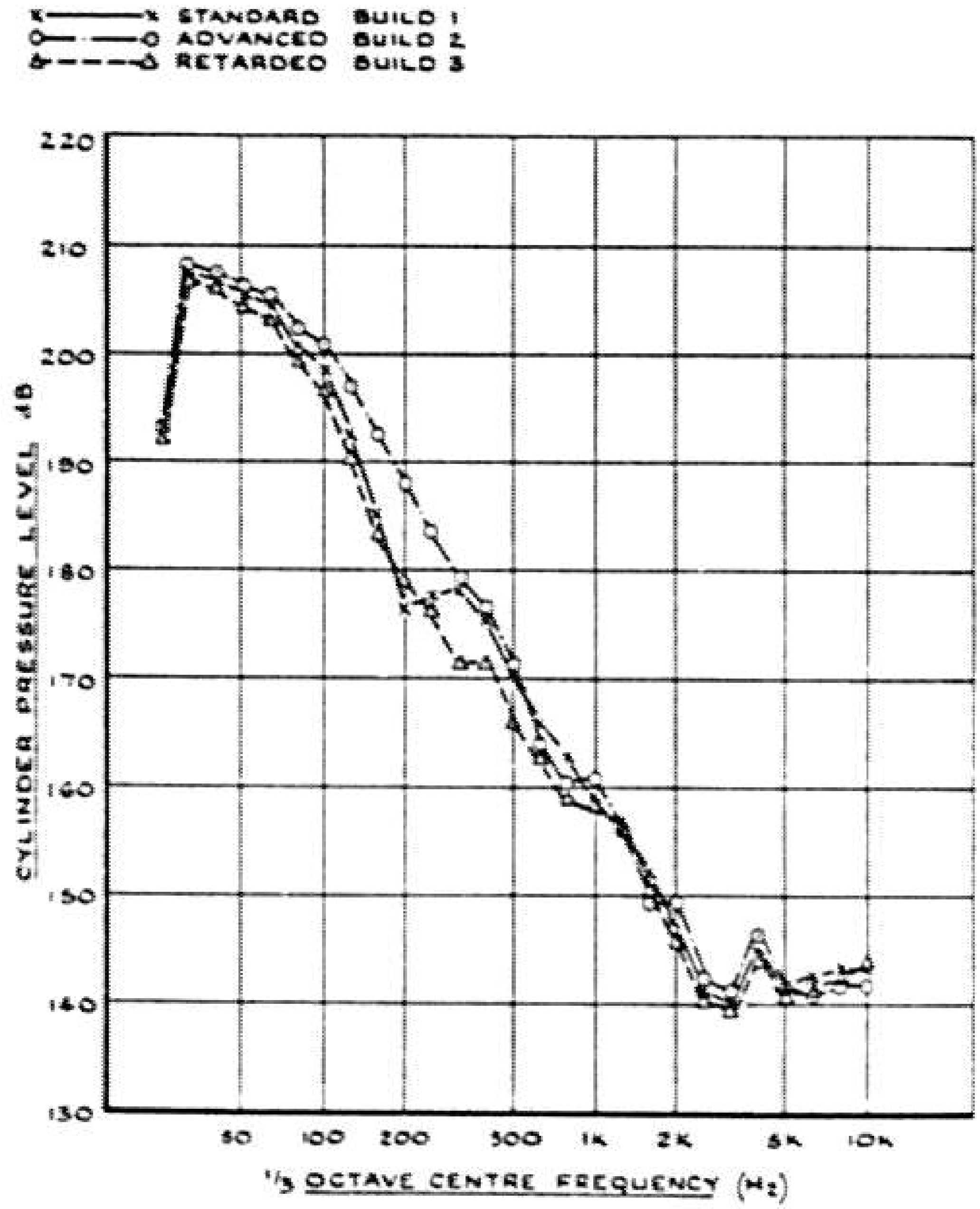


FIGURE 5-11. PEUGEOT XD2 EFFECT OF TIMING ON CYLINDER PRESSURE SPECTRA FULL LOAD 20 REV/S

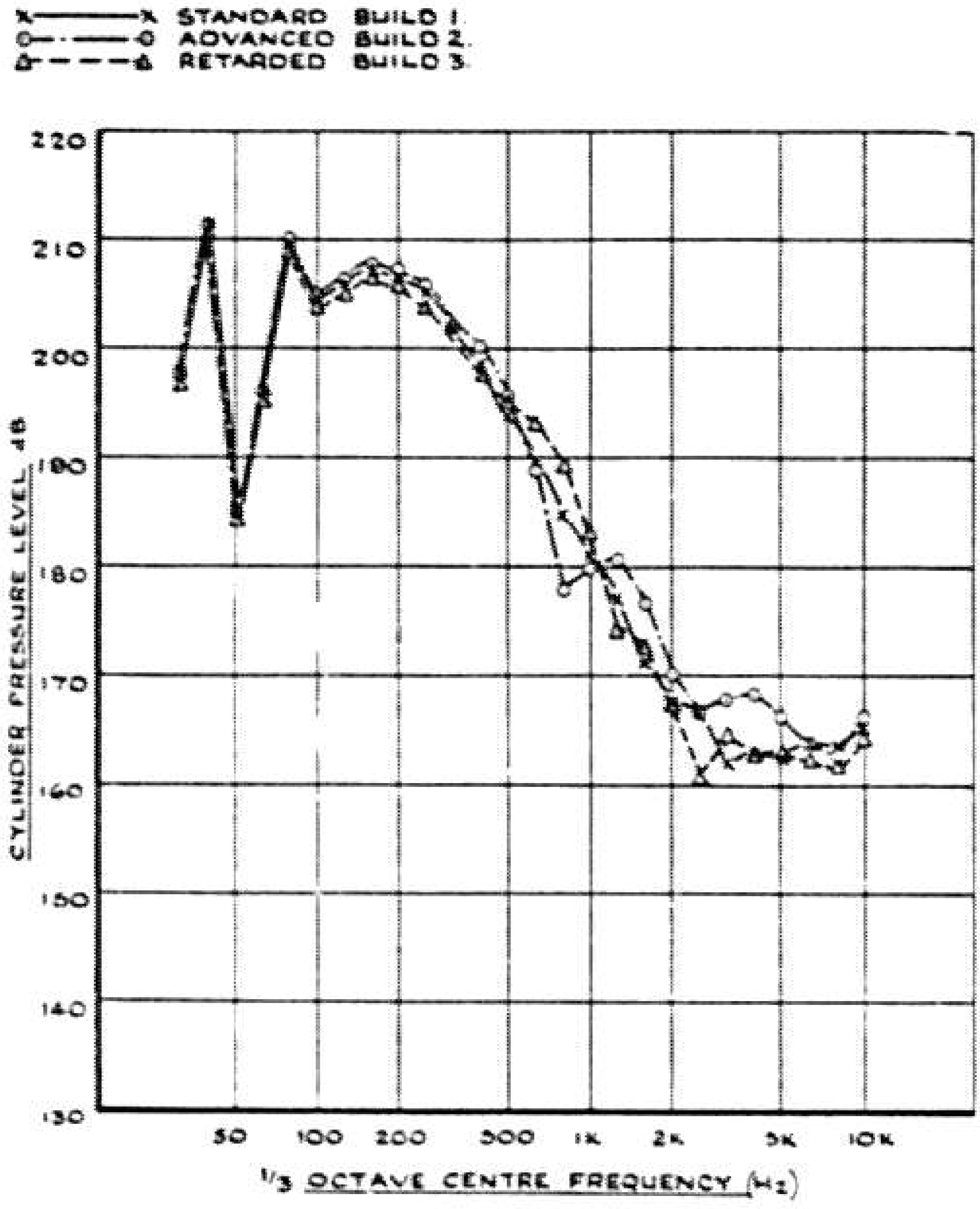


FIGURE 5-12. PEUGEOT XD2 EFFECT OF TIMING ON CYLINDER PRESSURE SPECTRA FULL LOAD 75 REV/S

OVERALL LEVEL =84.2dBA PEUGEOT XD2, 30REV/S, RHS

1/3 Oct BAND Hz	S.P.L. dBL	COMBUSTION NOISE dBL	MECHANICAL NOISE dBL
400	****	****	****
* 500	****	****	****
630	75.2	73.0	69.6
* 800	71.2	52.0	71.1
1000	70.0	68.0	65.6
1250	72.6	68.0	70.8
1600	76.8	74.0	73.5
2000	73.6	73.4	60.9
2500	****	****	****
3150	****	****	****
4000	69.6	64.6	67.9
CALC. LEVEL dBA	81.9	79.7	78.6
CORR. LEVEL dBA	84.2	81.7	80.6

FIGURE 5-13. PEUGEOT XD2 COMBUSTION/MECHANICAL NOISE BREAKDOWN* STANDARD TIMING

OVERALL LEVEL =85.6dBA PEUGEOT XD2. 30REV/S, LHS

1/3 Oct BAND Hz	S.P.L. dBL	COMBUSTION NOISE dBL	MECHANICAL NOISE dBL
400	####	####	####
* 500	69.2	68.9	57.0
* 630	71.8	68.2	69.3
800	70.4	66.3	68.3
1000	74.2	68.4	72.9
1250	77.0	74.2	73.8
1600	76.4	73.9	72.8
2000	76.2	71.8	74.2
2500	####	####	####
3150	####	####	####
4000	68.2	65.1	65.3
CALC. LEVEL dBA	83.1	80.2	80.8
CORR. LEVEL dBA	85.6	82.2	82.9

FIGURE 5-14. PEUGEOT XD2 COMBUSTION/MECHANICAL NOISE BREAKDOWN* STANDARD TIMING

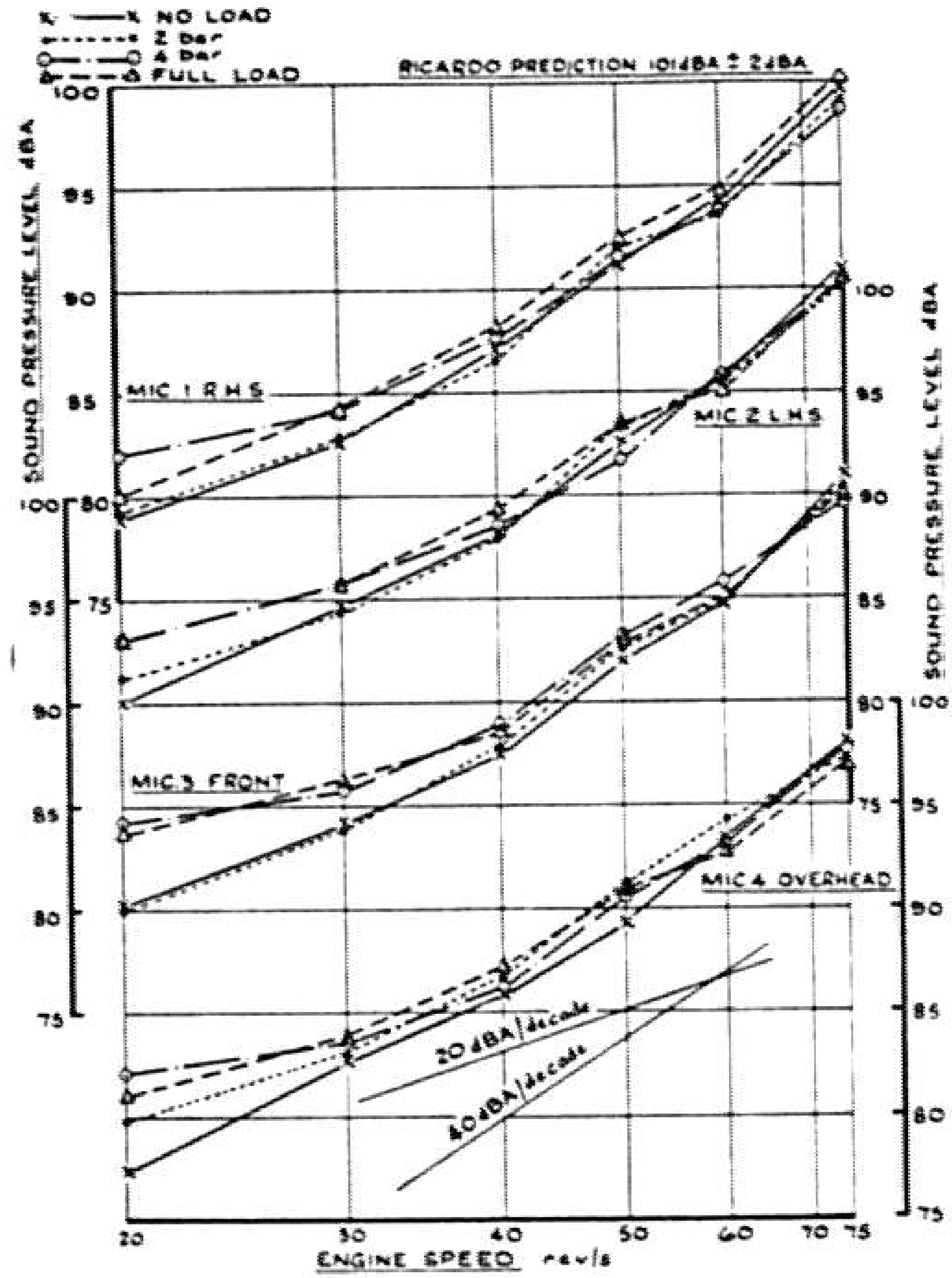


FIGURE 5-15. PEUGEOT XD2 NOISE TESTS OVER THE LOAD AND SPEED RANGES STANDARD BUILD

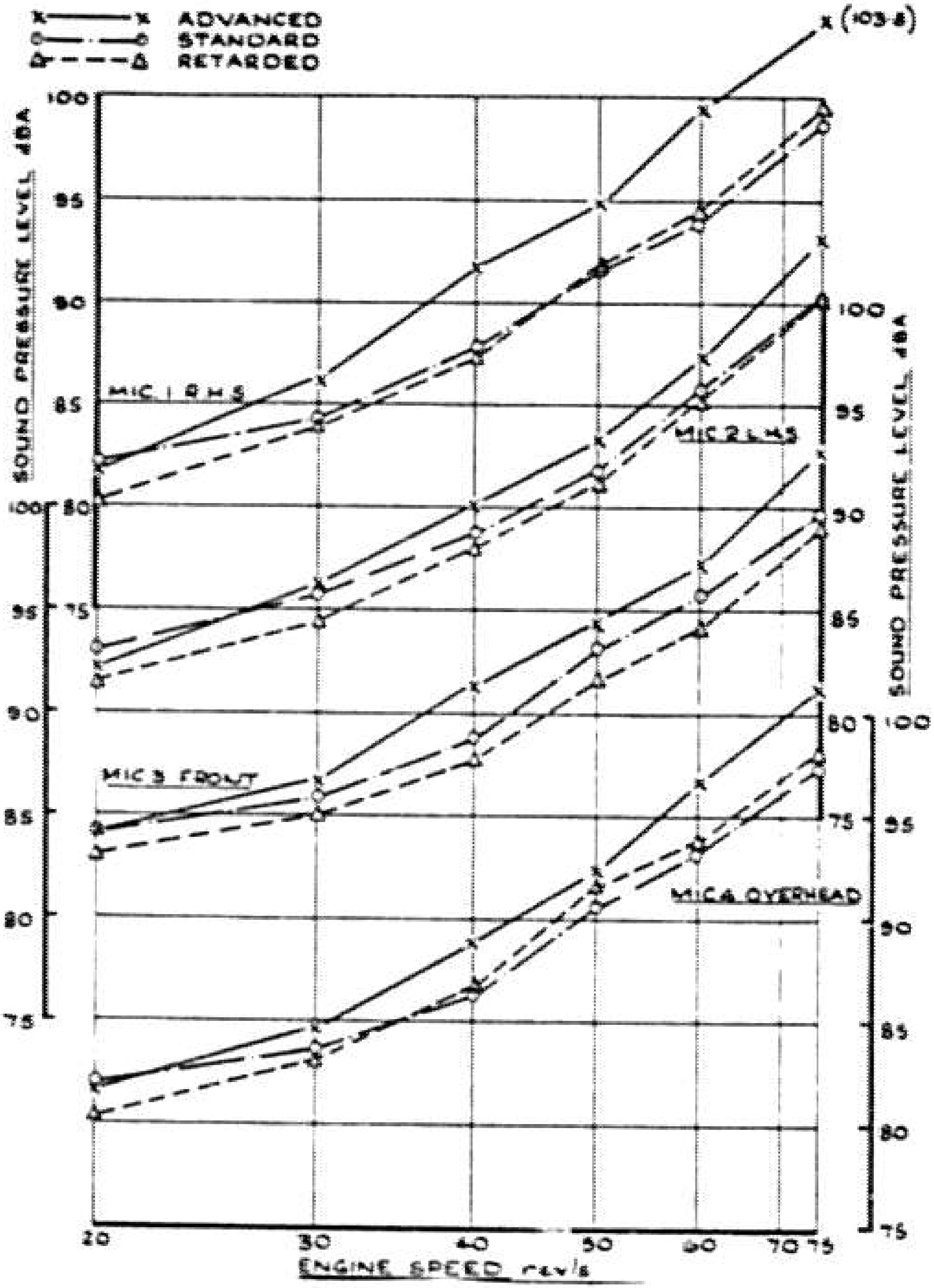


FIGURE 5-16. PEUGEOT XD2 EFFECT OF TIMING ON FULL LOAD NOISE LEVELS

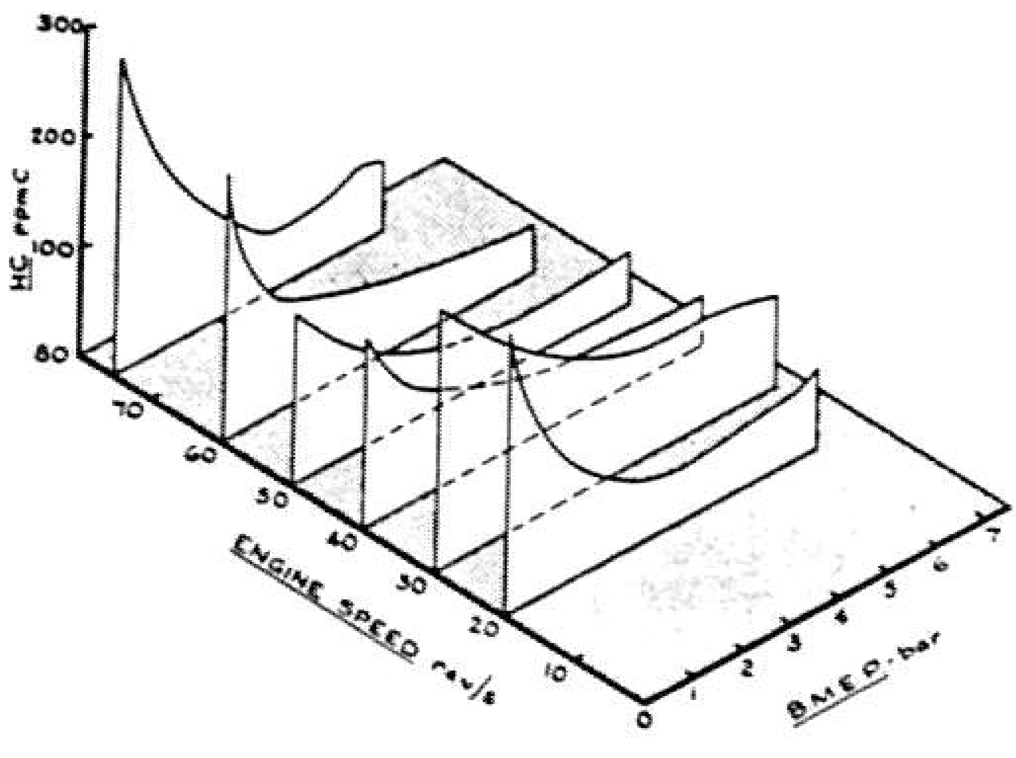


FIGURE 5-17. PEUGEOT XD2 HYDROCARBON EMISSIONS OVER THE LOAD AND SPEED RANGES STANDARD BUILD

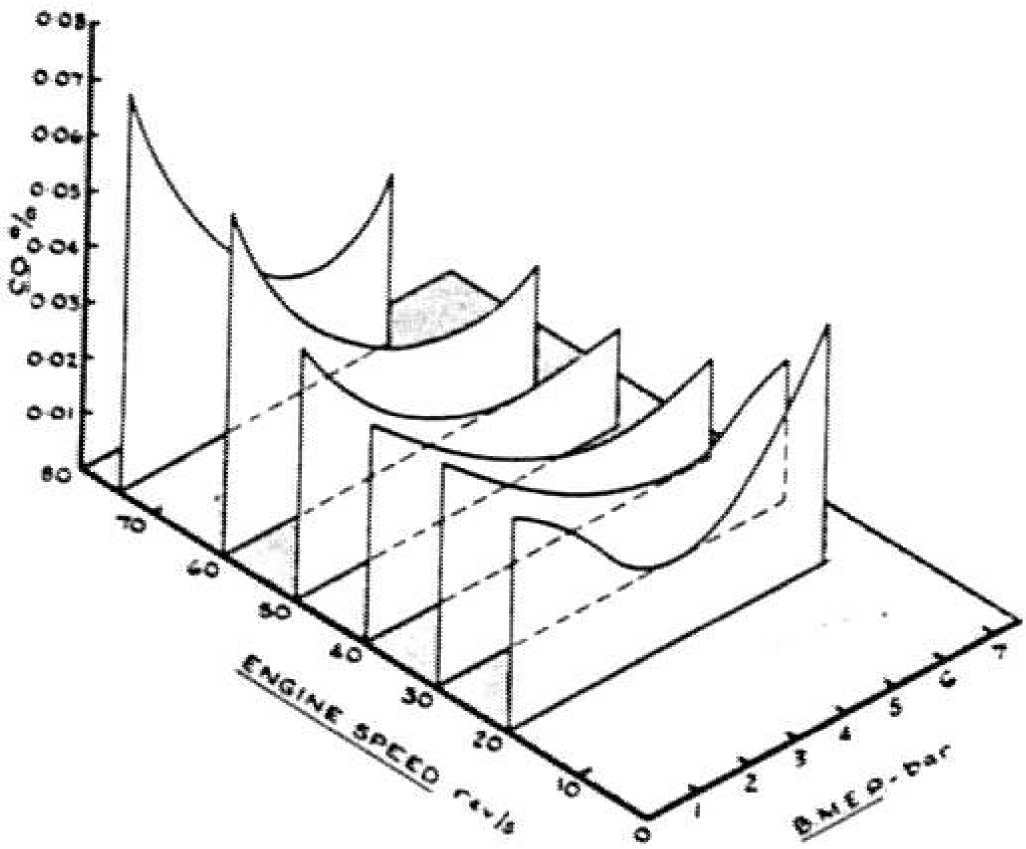


FIGURE 5-18. PEUGEOT XD2 CO EMISSIONS OVER THE LOAD AND SPEED RANGES STANDARD BUILD

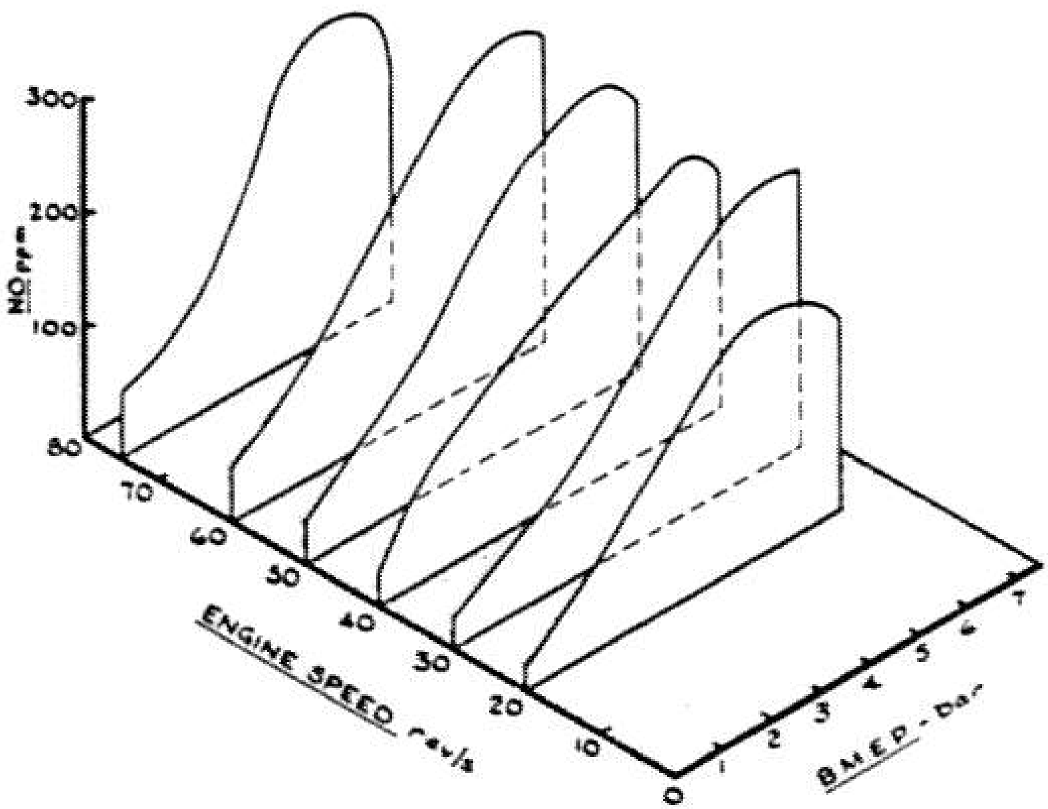


FIGURE 5-19. PEUGEOT XD2 NO EMISSIONS OVER THE LOAD AND SPEED RANGES STANDARD BUILD

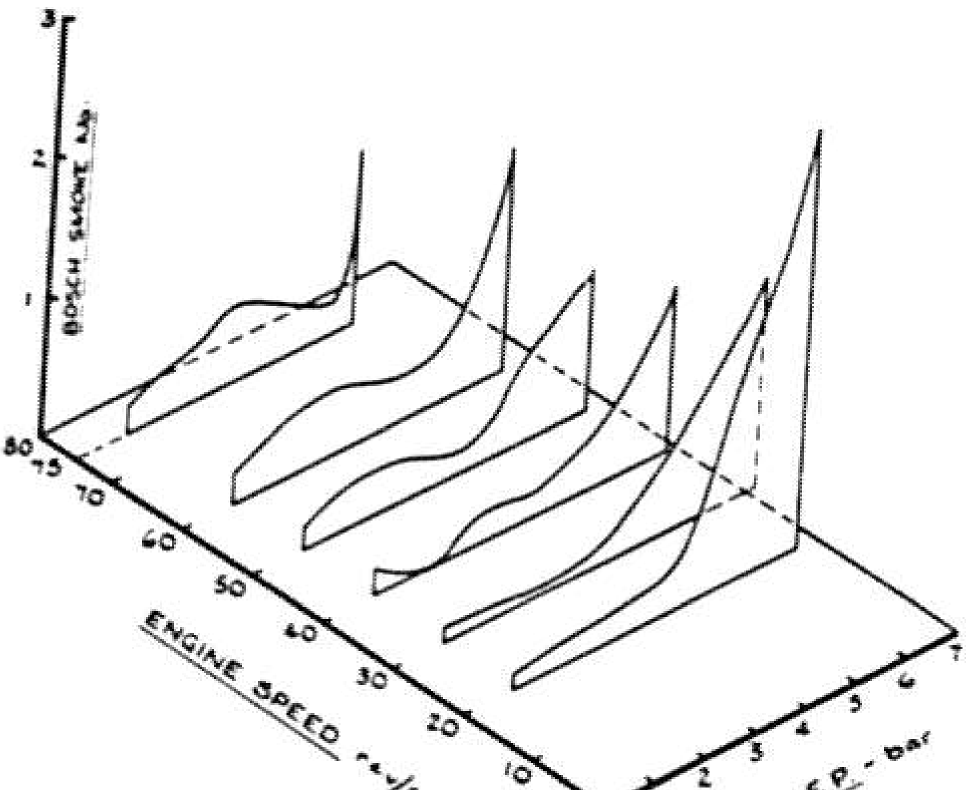


FIGURE 5-20. PEUGEOT XD2 SMOKE OVER THE LOAD AND SPEED RANGES BUILD 1

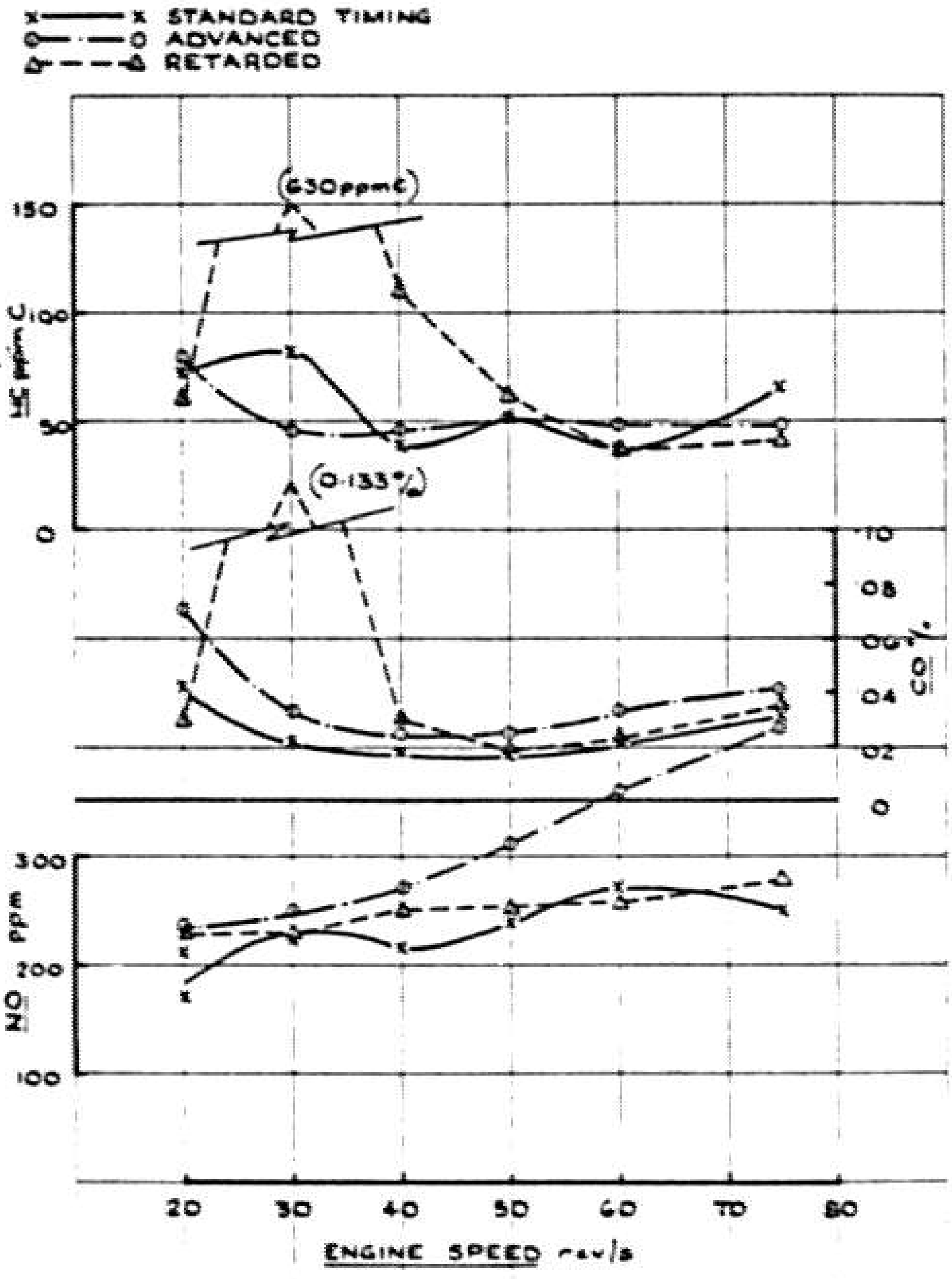


FIGURE 5-21. PEUGEOT XD2 EFFECT OF TIMING ON FULL LOAD EXHAUST EMISSIONS

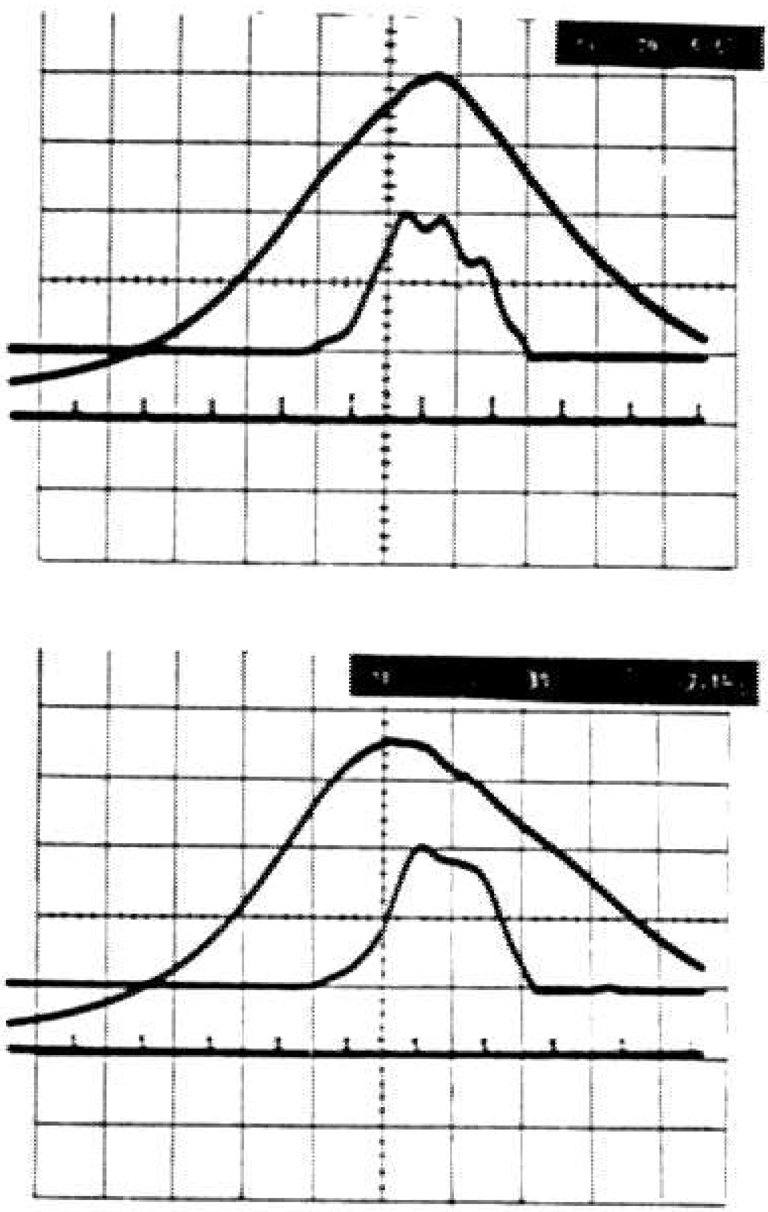


FIGURE 5-22. PEUGEOT XD2 CYLINDER PRESSURE AND NEEDLE LIFT DIAGRAMS BUILD 1, FULL LOAD, 20 AND 30 REV/S

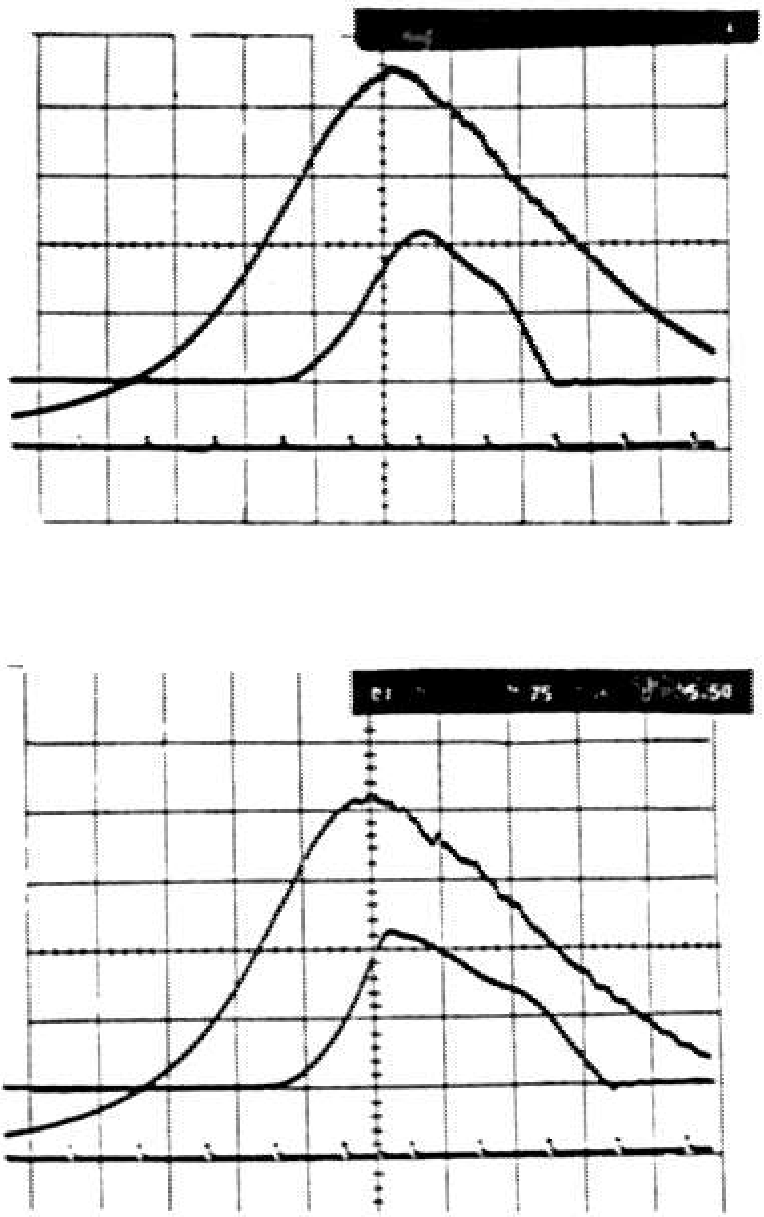


FIGURE 5-23. PEUGEOT XD2 CYLINDER PRESSURE AND NEEDLE LIFT DIAGRAMS BUILD 1, FULL LOAD, 50 AND 75 REV/S

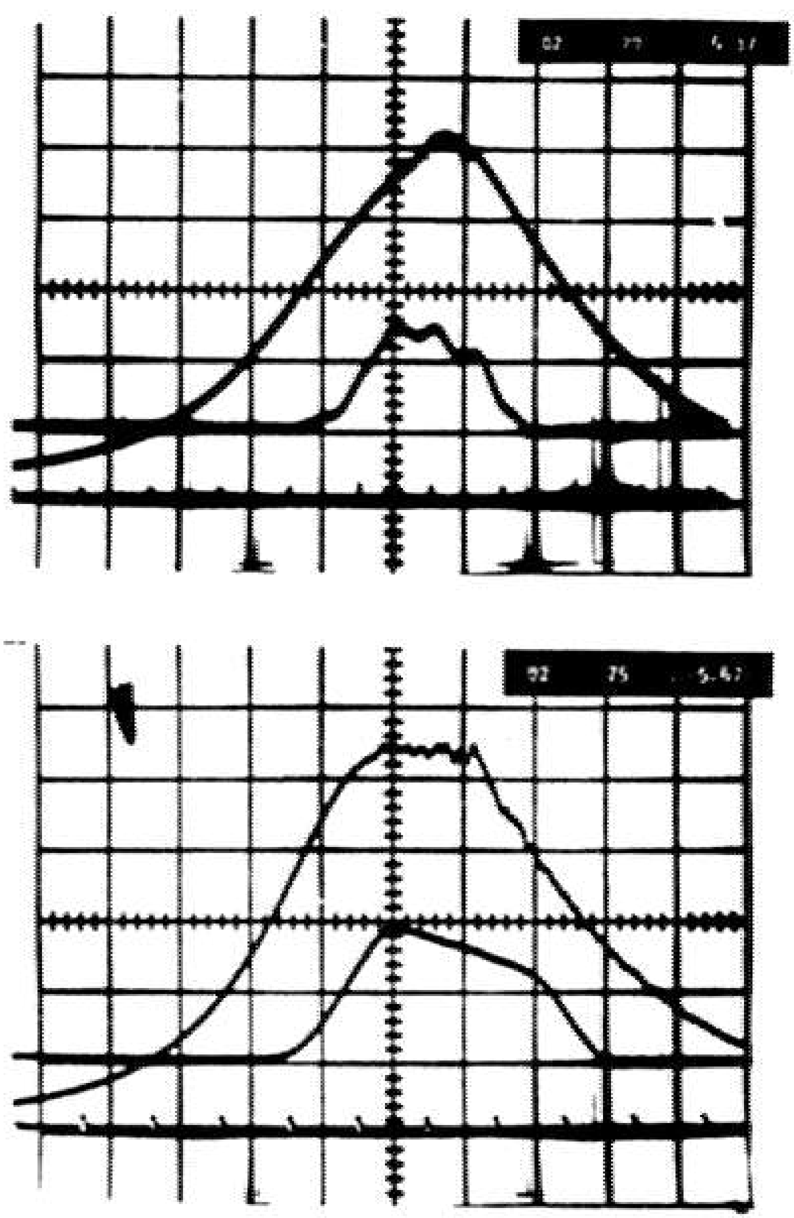


FIGURE 5-24. PEUGEOT XD2 CYLINDER PRESSURE AND NEEDLE LIFT DIAGRAMS BUILD 2, FULL LOAD, 20 AND 75 REV/S

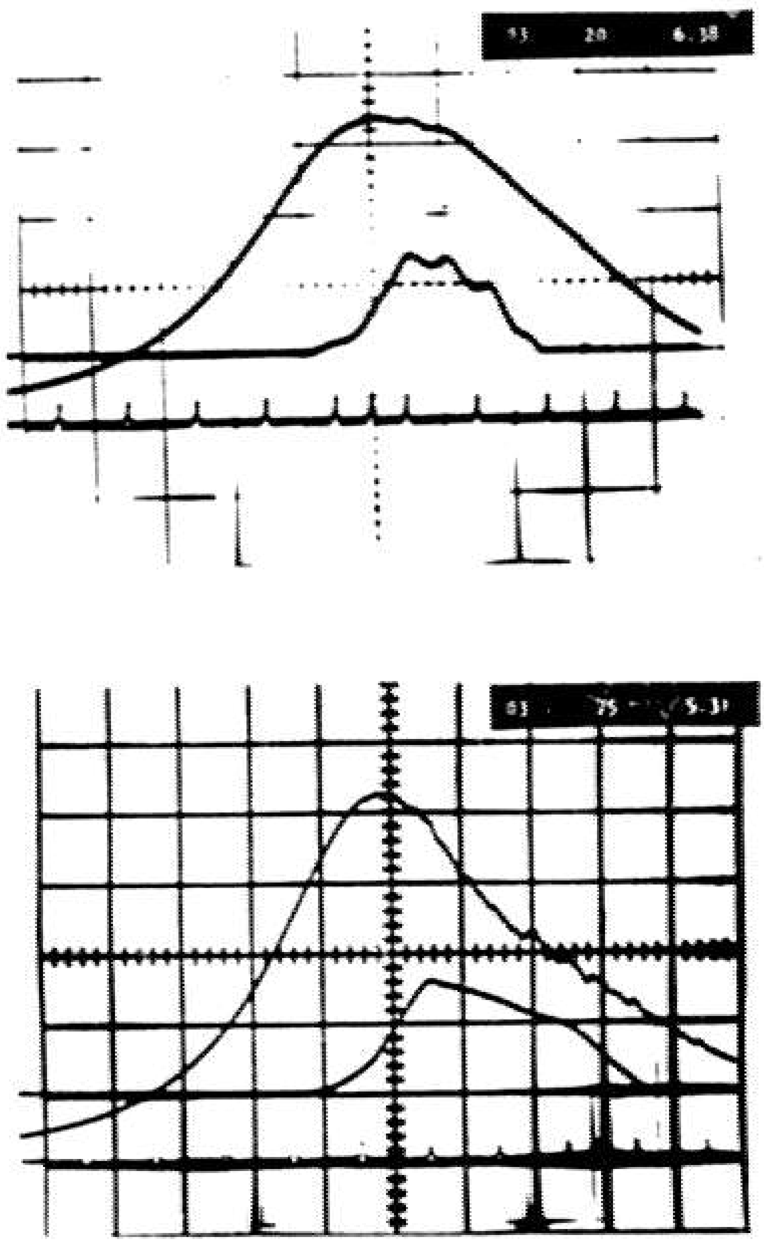


FIGURE 5-25. PEUGEOT XD2 CYLINDER PRESSURE AND NEEDLE LIFT DIAGRAMS BUILD 3, FULL LOAD, 20 AND 75 REV/S

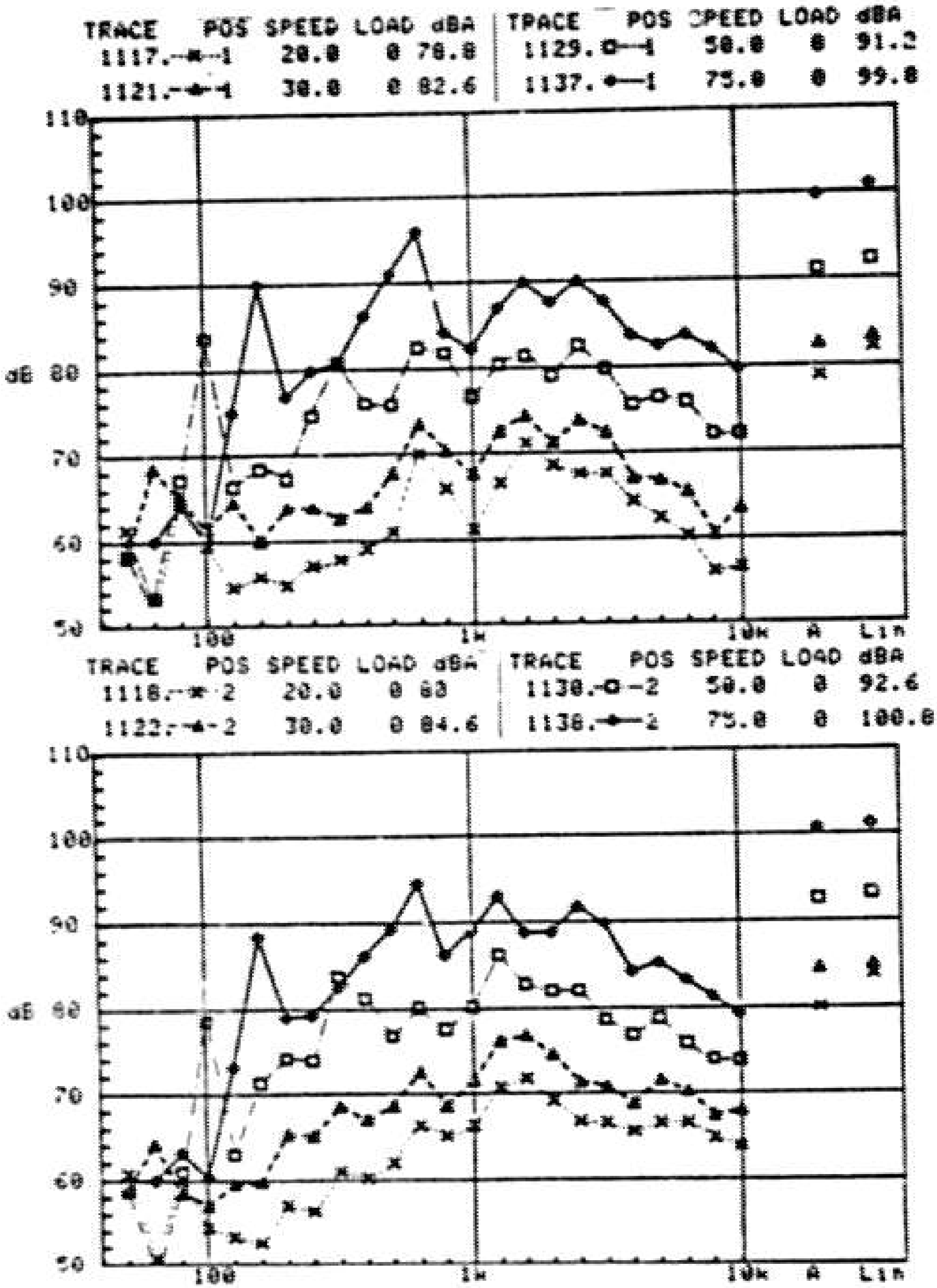


FIGURE 5-26. PEUGEOT XD2 EFFECT OF SPEED - NO LOAD, MICROPHONE POSITIONS 1 AND 2

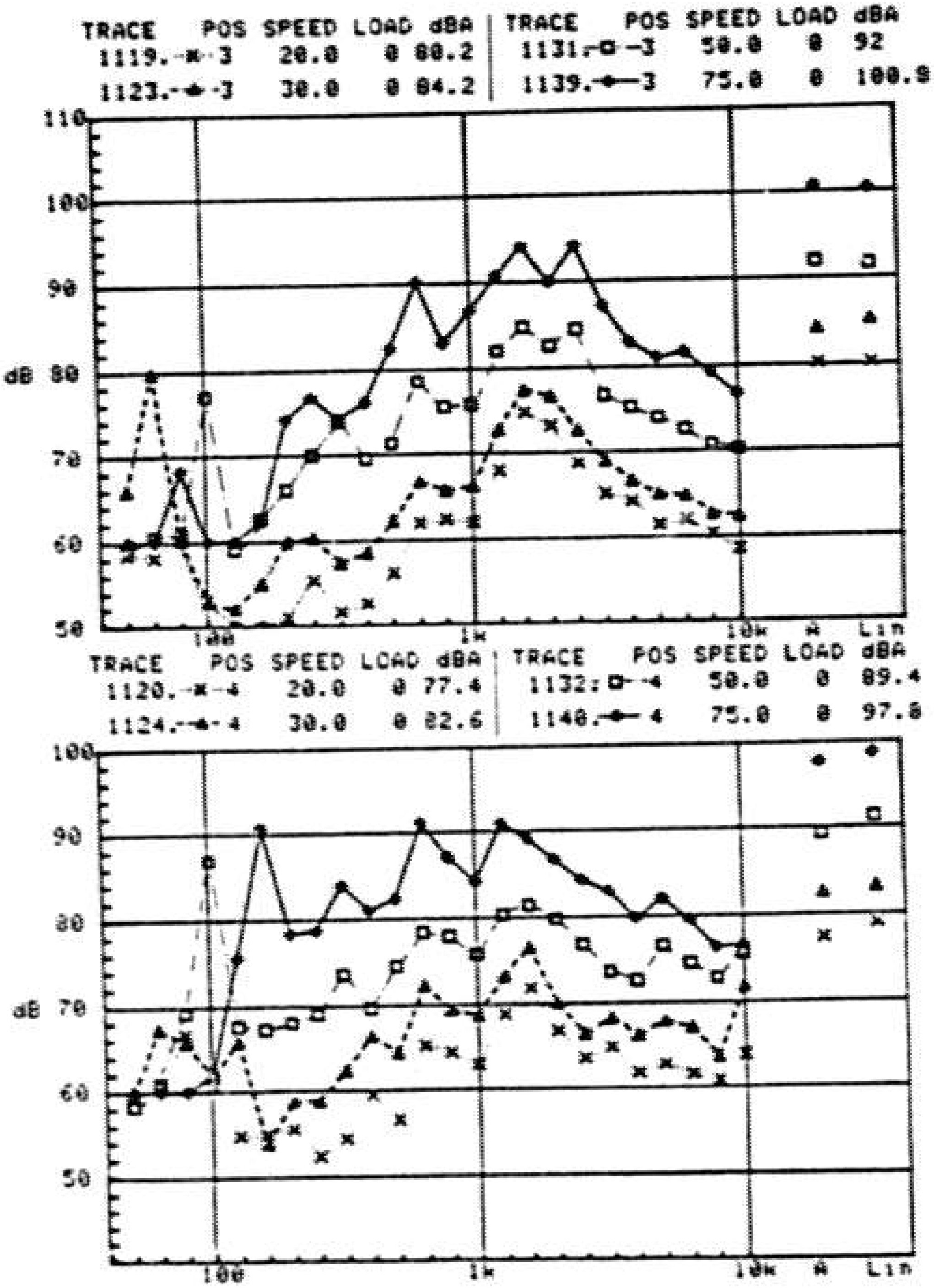


FIGURE 5-27. PEUGEOT XD2 EFFECT OF SPEED - NO LOAD, MICROPHONE POSITIONS 3 AND 4

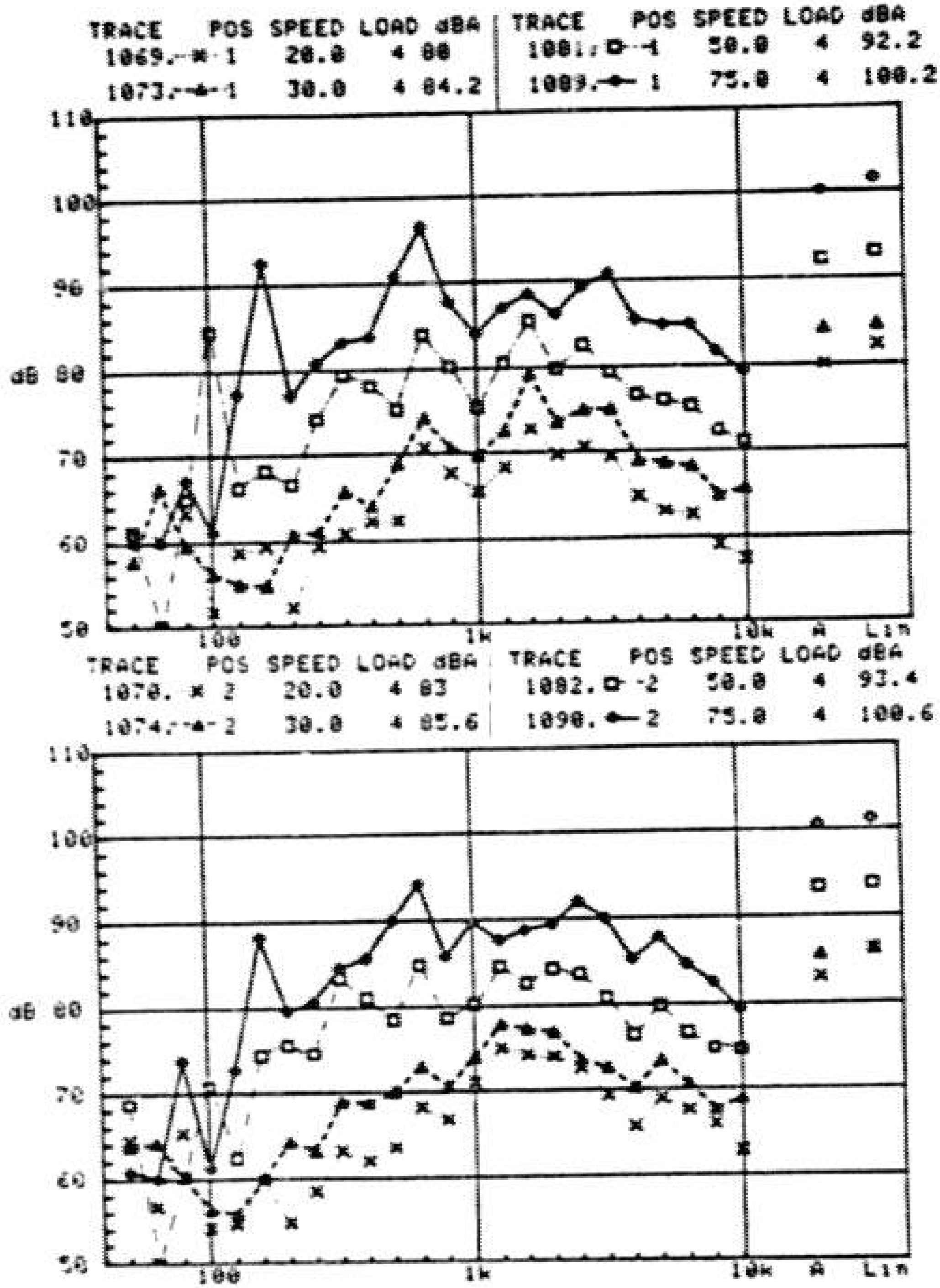


FIGURE 5-28. PEUGEOT XD2 EFFECT OF SPEED, BAR BMEP, MICROPHONE POSITIONS 1 AND 2

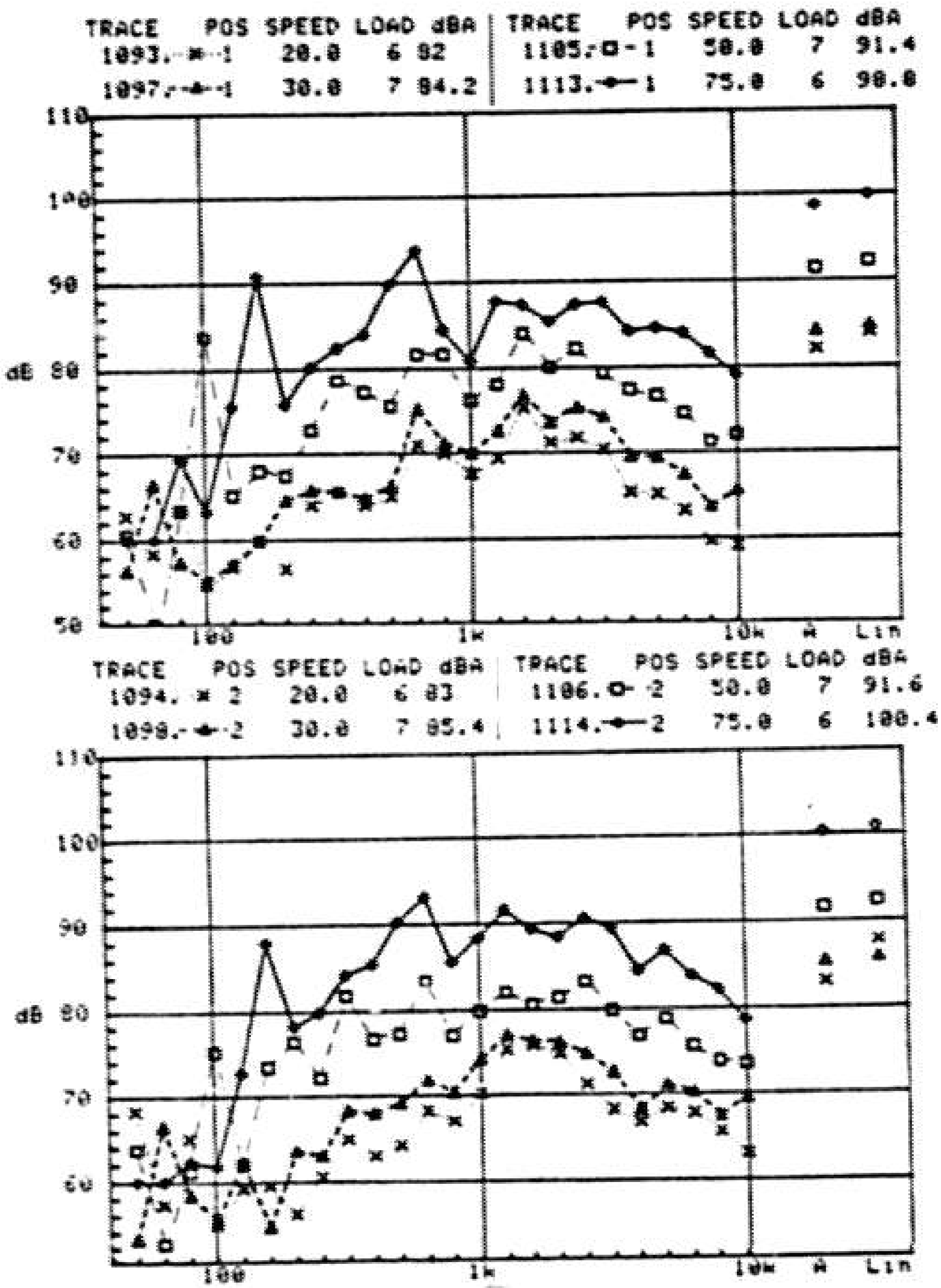


FIGURE 5-29. PEUGEOT XD2 EFFECT OF SPEED - FULL LOAD, MICROPHONE POSITIONS 1 AND 2

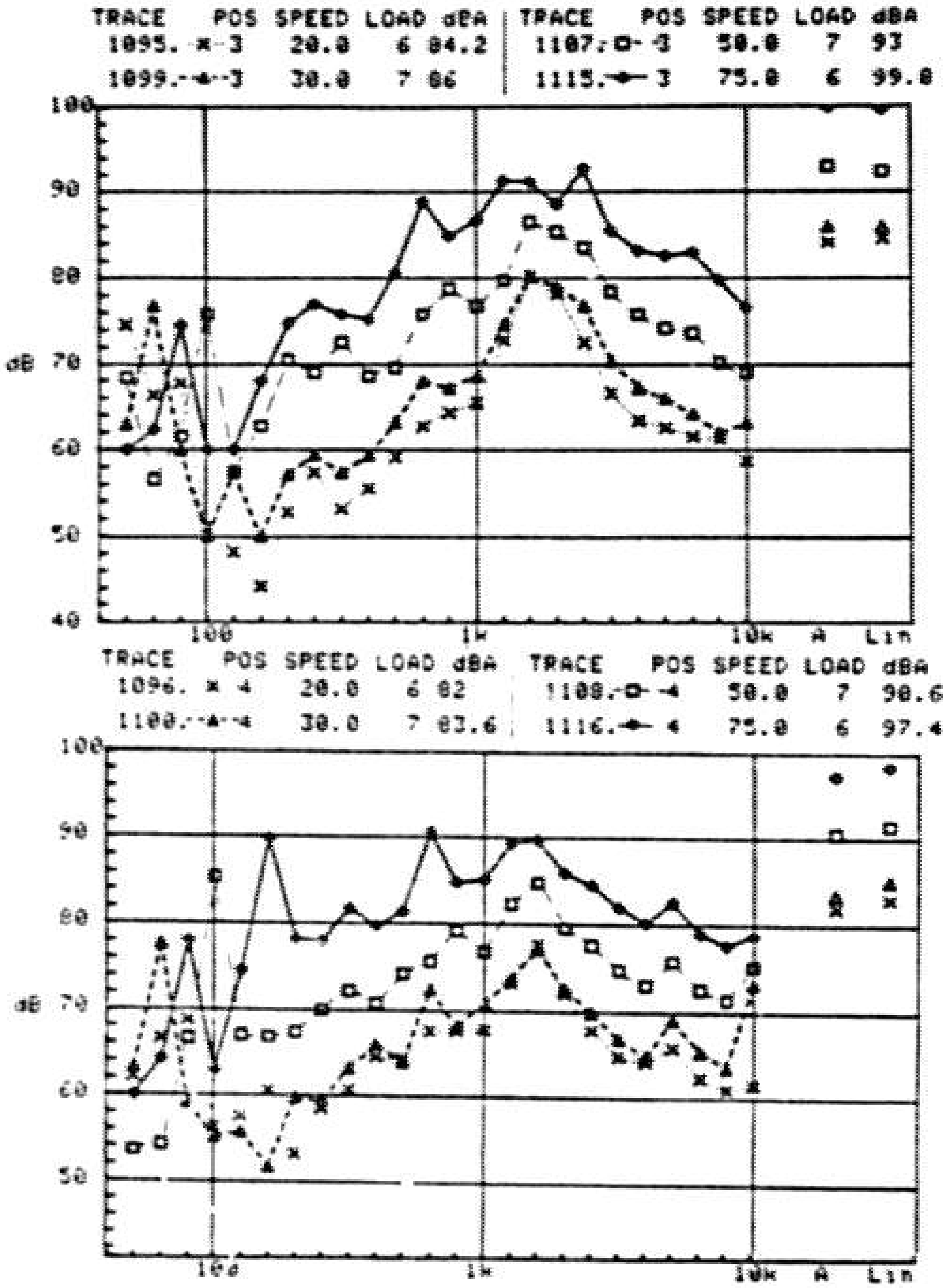


FIGURE 5-30. PEUGEOT XD2 EFFECT OF SPEED - FULL LOAD, MICROPHONE POSITIONS 3 AND 4

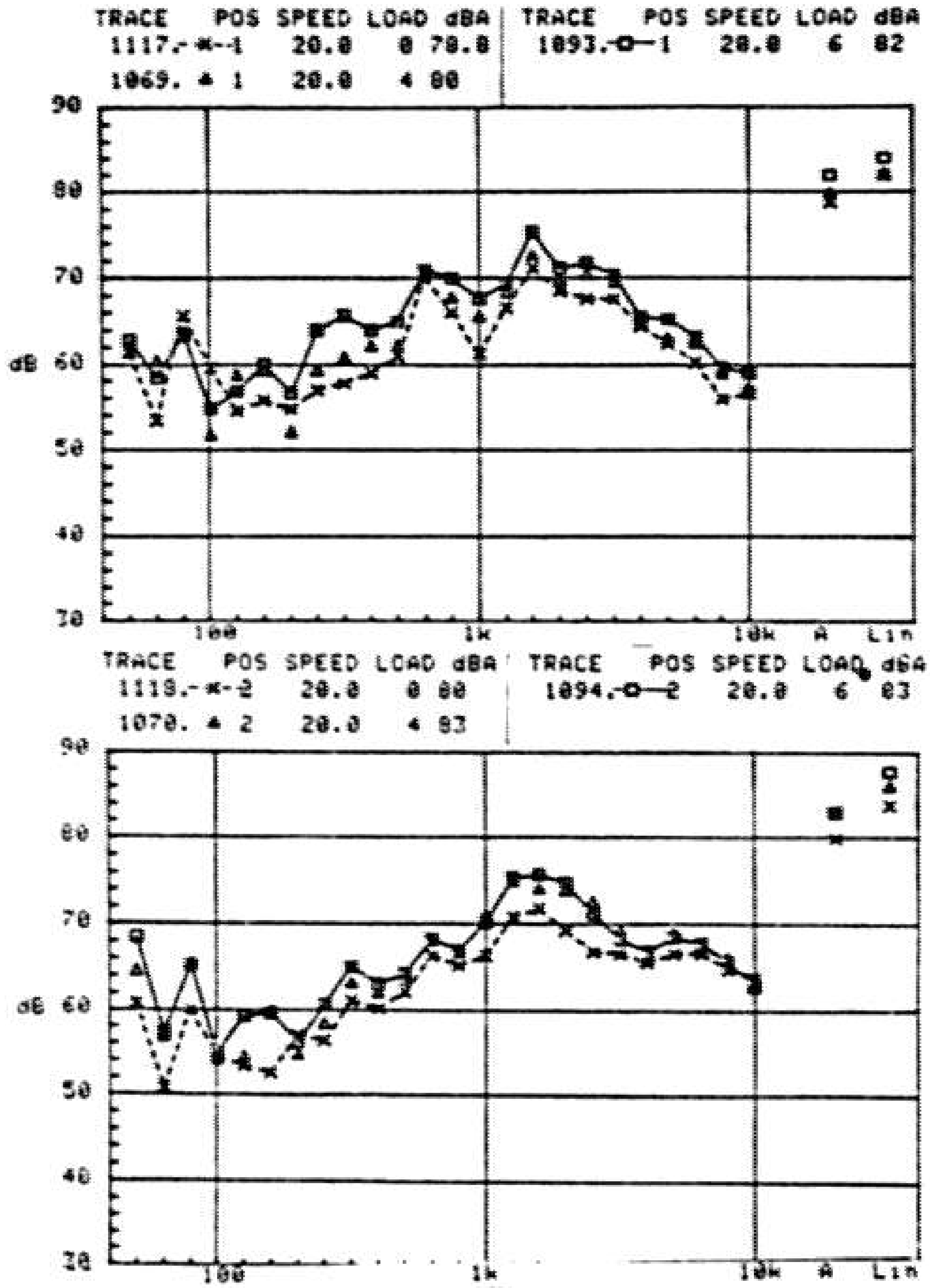


FIGURE 5-31. PEUGEOT XD2 EFFECT OF LOAD, 20 REV/S, MICROPHONE POSITIONS 1 AND 2

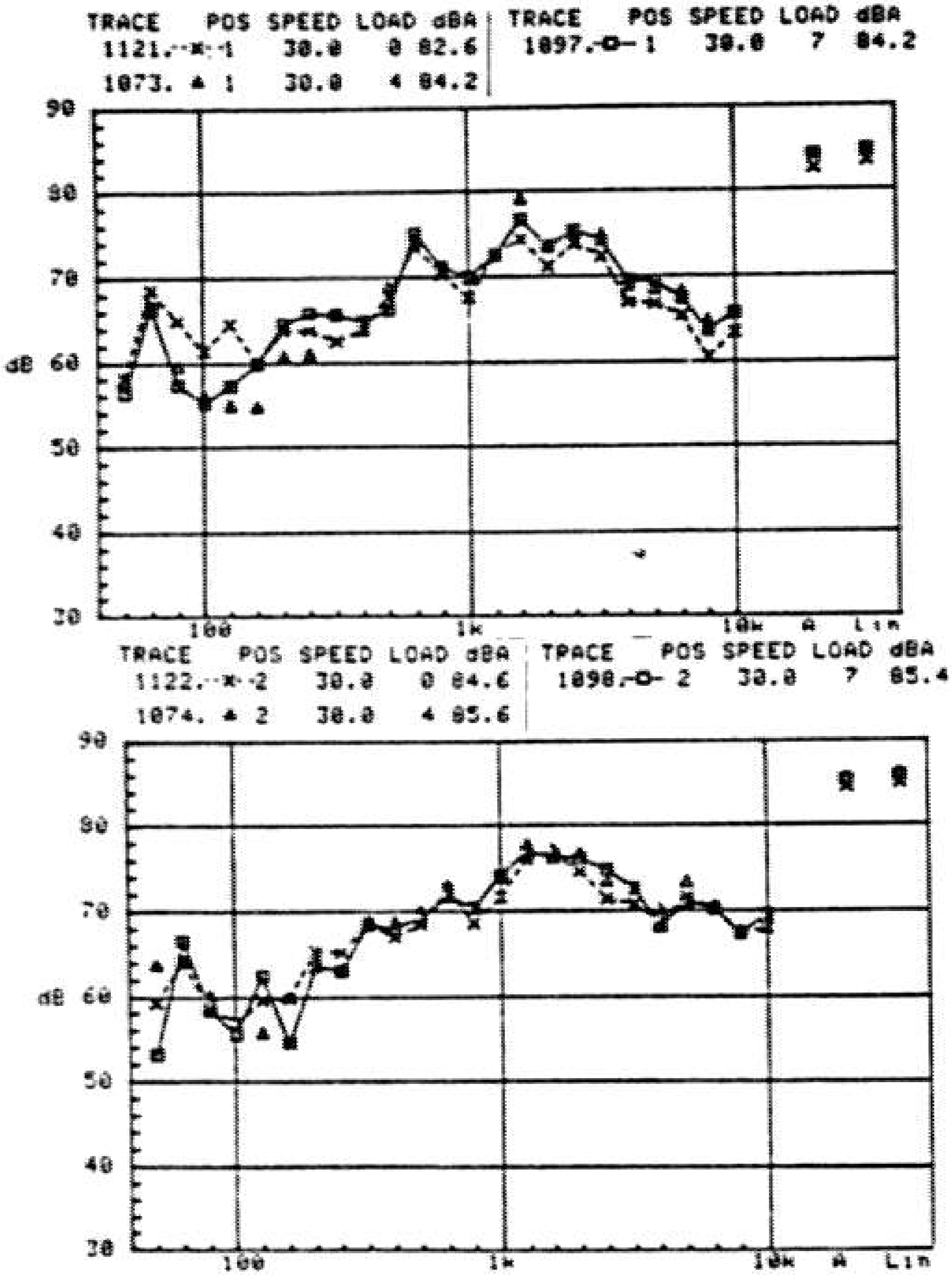


FIGURE 5-32. PEUGEOT XD2 EFFECT OF LOAD, 30 REV/S, MICROPHONE POSITIONS 1 AND 2

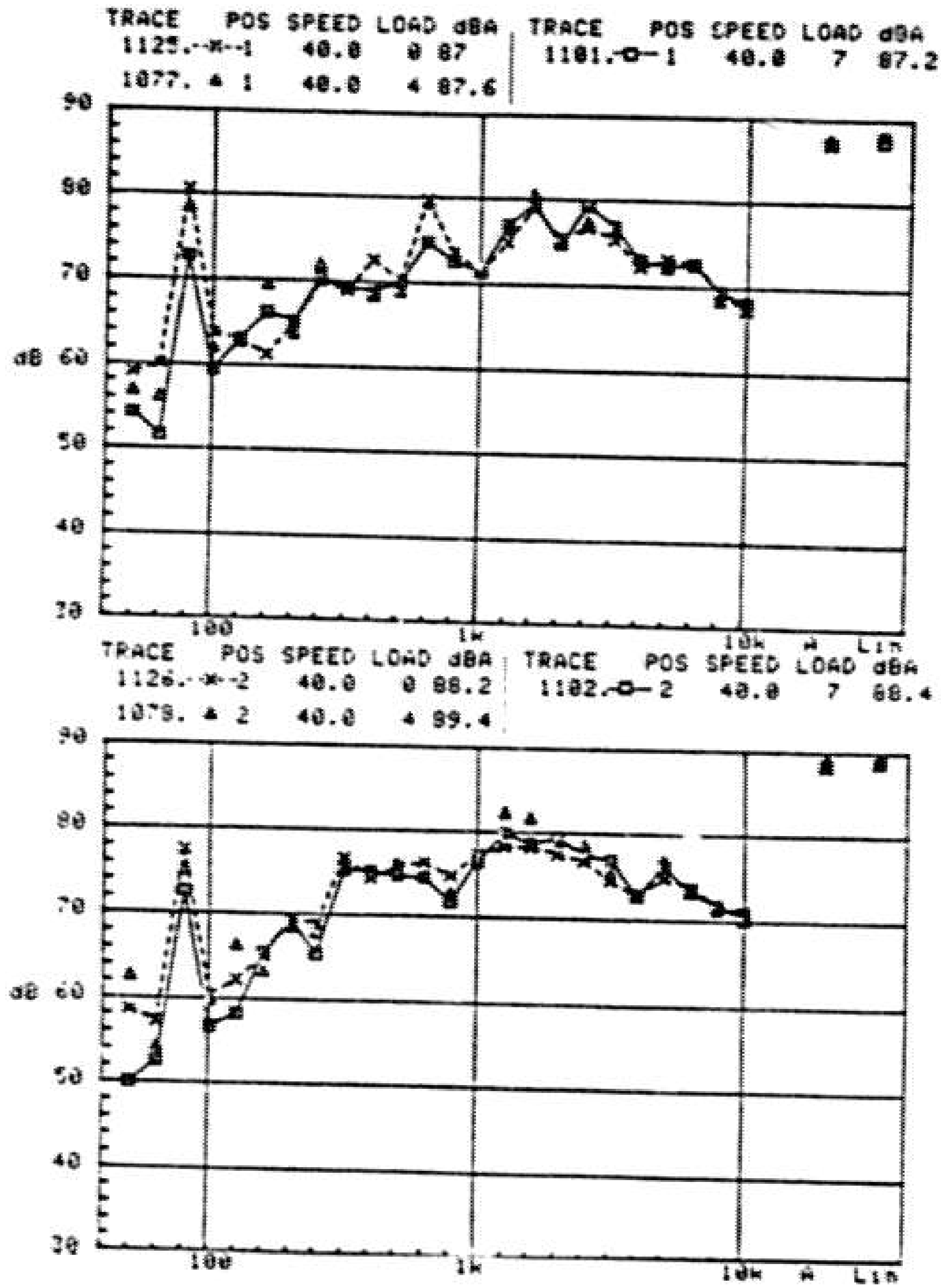


FIGURE 5-33. PEUGEOT XD2 EFFECT OF LOAD, 40 REV/S, MICROPHONE POSITIONS 1 AND 2

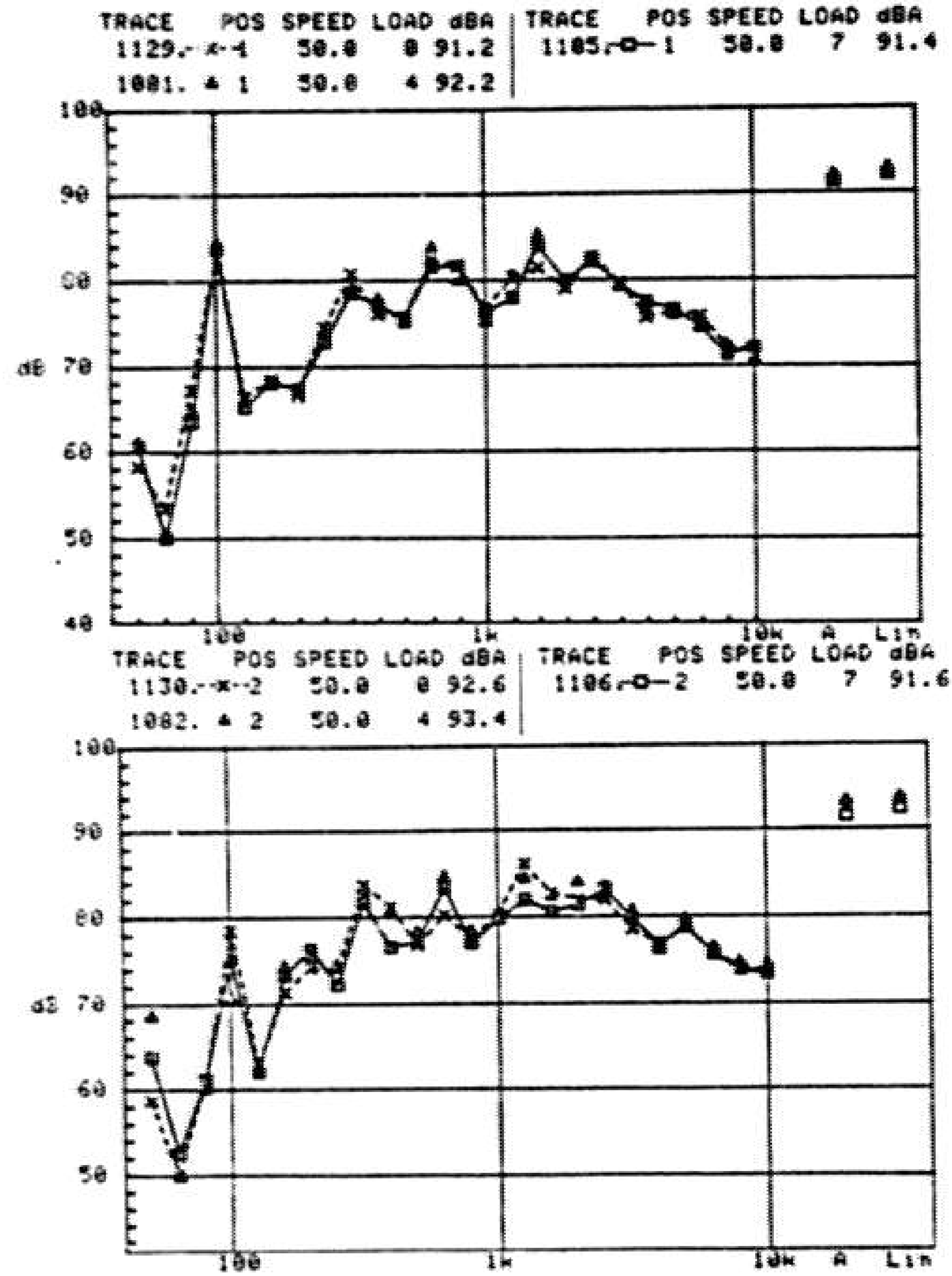


FIGURE 5-34. PEUGEOT XD2 EFFECT OF LOAD, 50 REV/S, MICROPHONE POSITIONS 1 AND 2

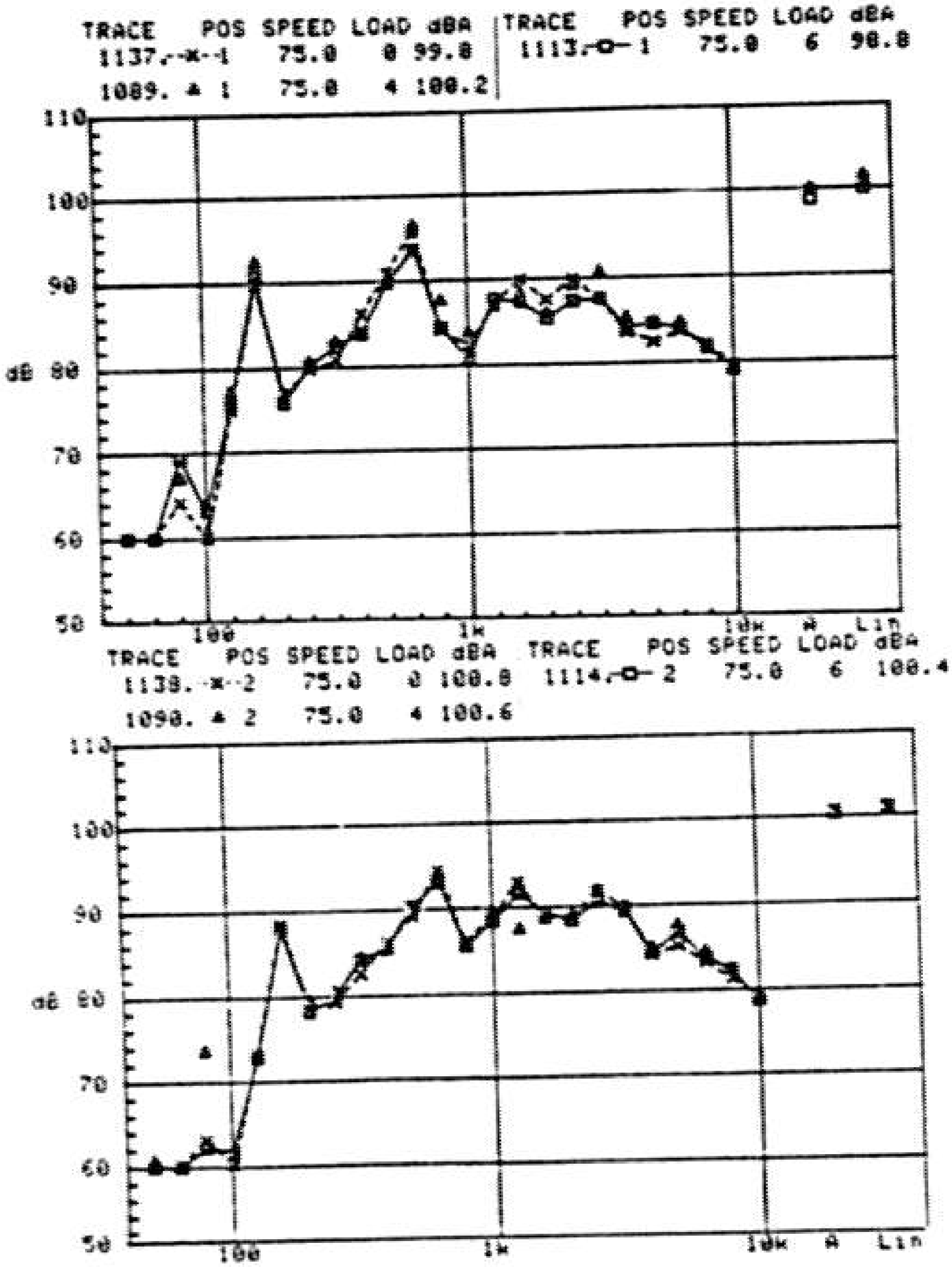


FIGURE 5-35. PEUGEOT XD2 EFFECT OF LOAD, 75 REV/S, MICROPHONE POSITIONS 1 AND 2

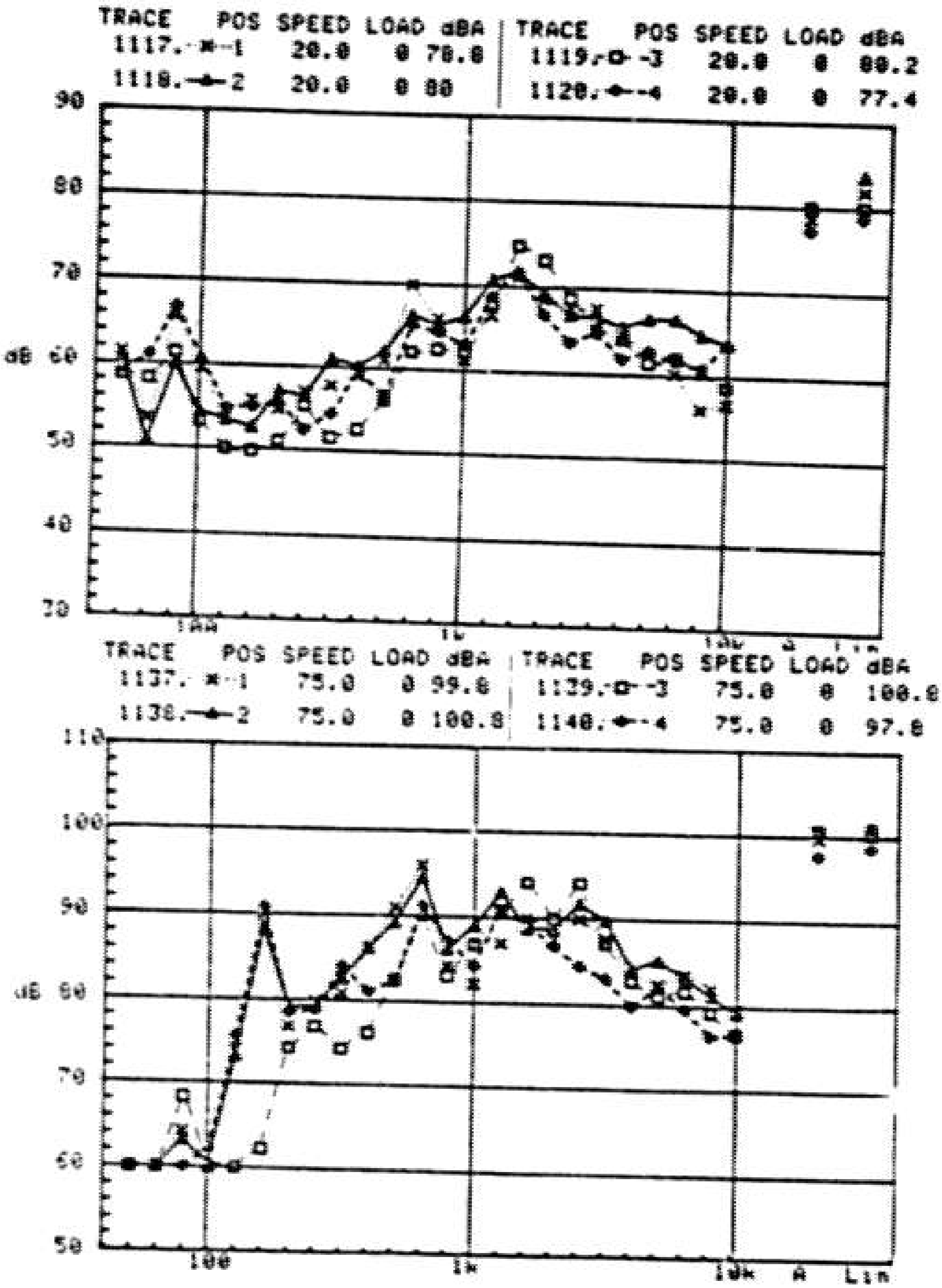


FIGURE 5-36. PEUGEOT XD2 NO LOAD SPECTRA AT 4 MICROPHONE POSITIONS 20 AND 75 REV/S

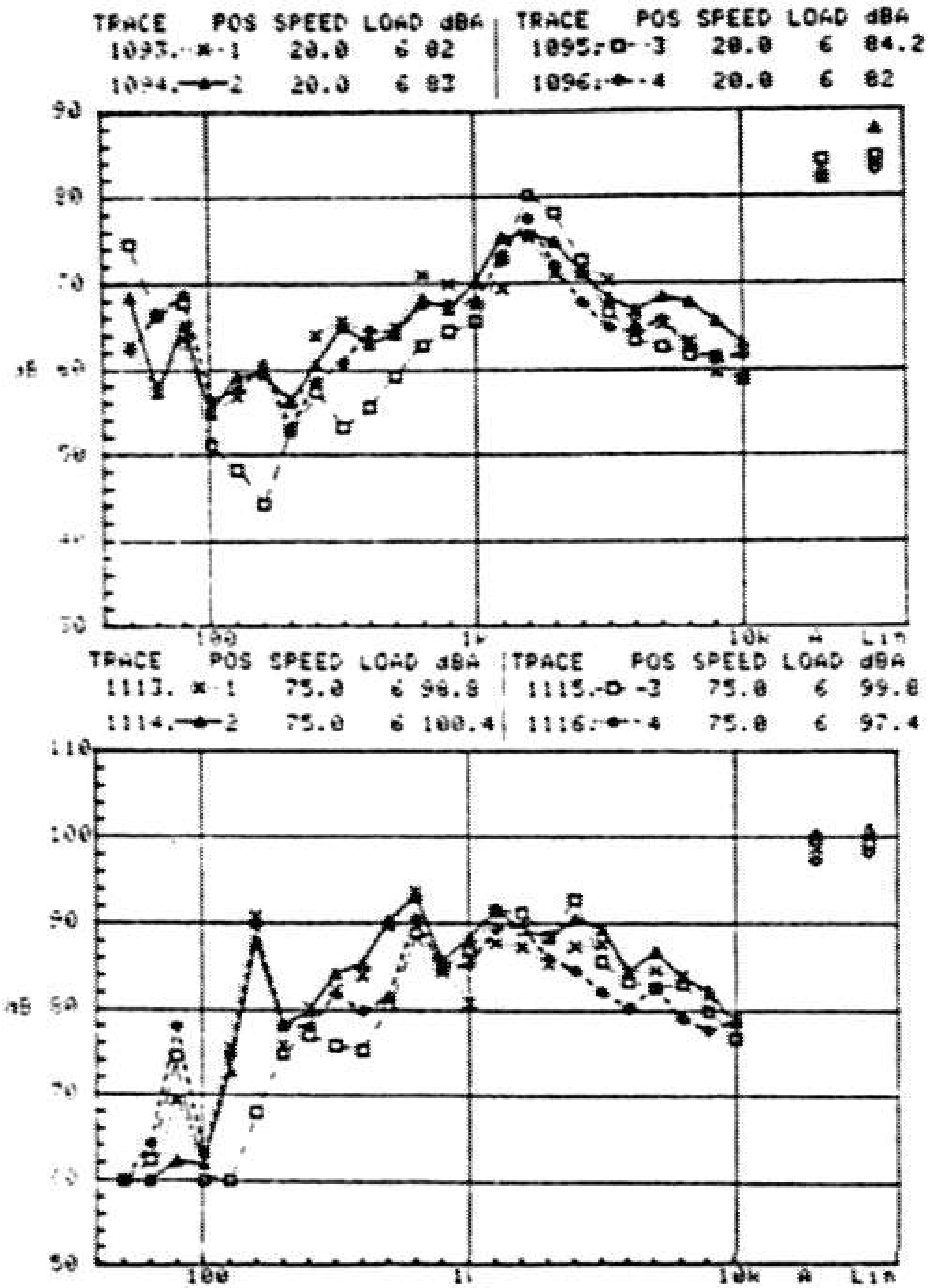


FIGURE 5-37. PEUGEOT XD2 FULL LOAD SPECTRA AT 4 MICROPHONE POSITIONS 20 AND 75 REV/S

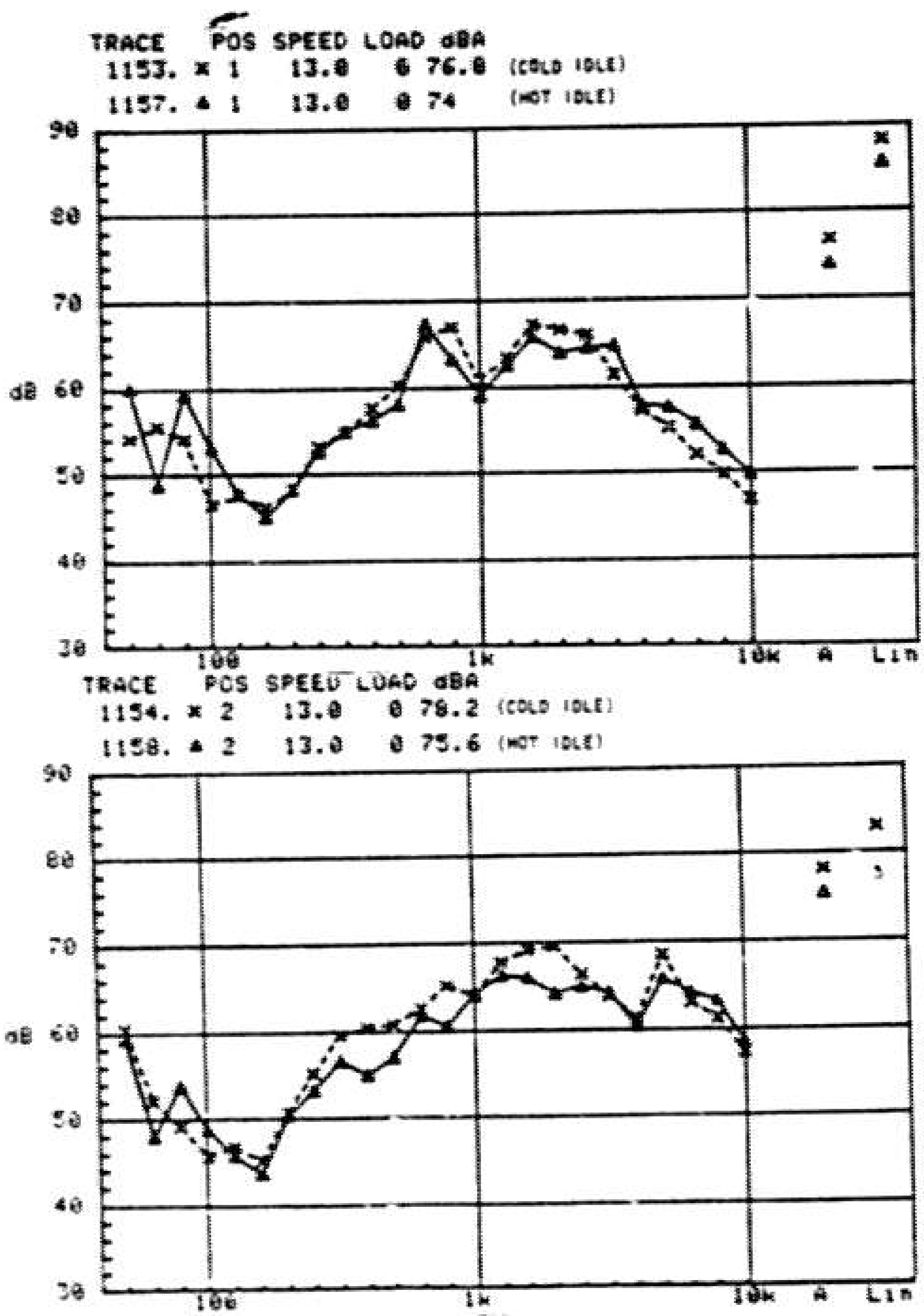


FIGURE 5-38 PEUGEOT XD2 HOT AND COLD IDLE,
RIGHT AND LEFT SIDES

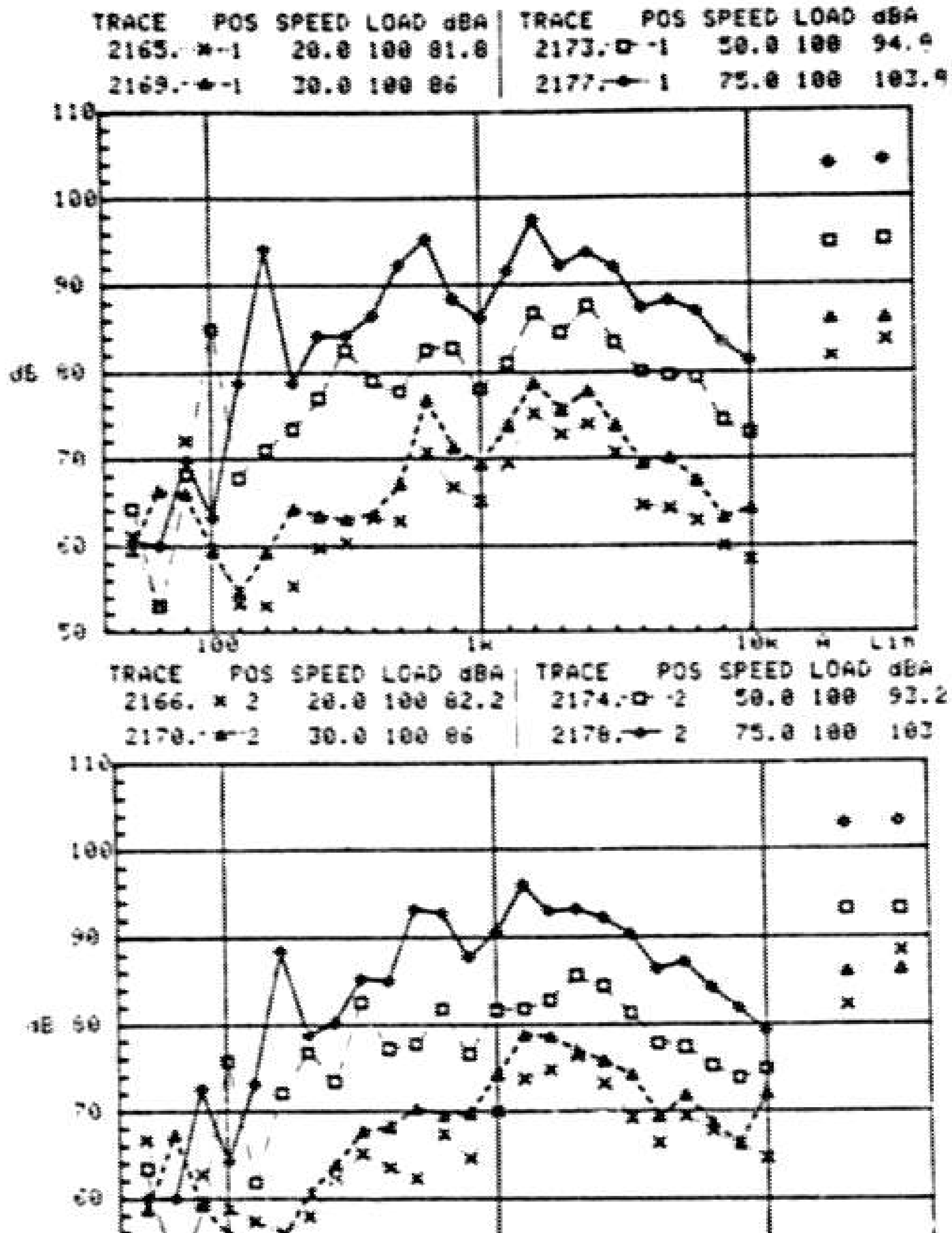


FIGURE 5-39. PEUGEOT XD2 EFFECT OF SPEED AT FULL LOAD, ADVANCED TIMING, MICROPHONE POSITIONS 1 AND 2

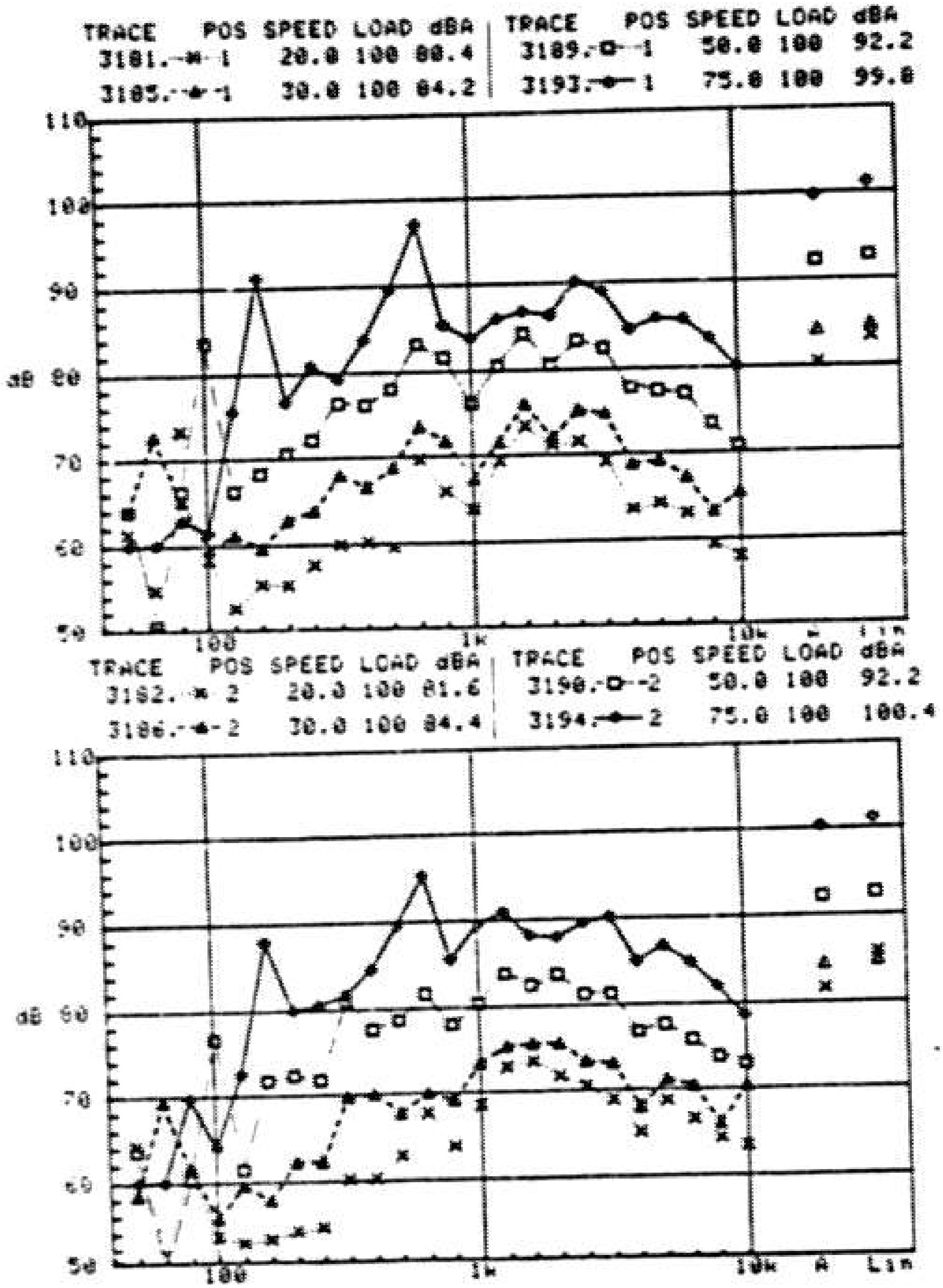


FIGURE 5-40. PEUGEOT XD2 EFFECT OF SPEED AT FULL LOAD, RETARDED TIMING, MICROPHONE POSITIONS 1 AND 2

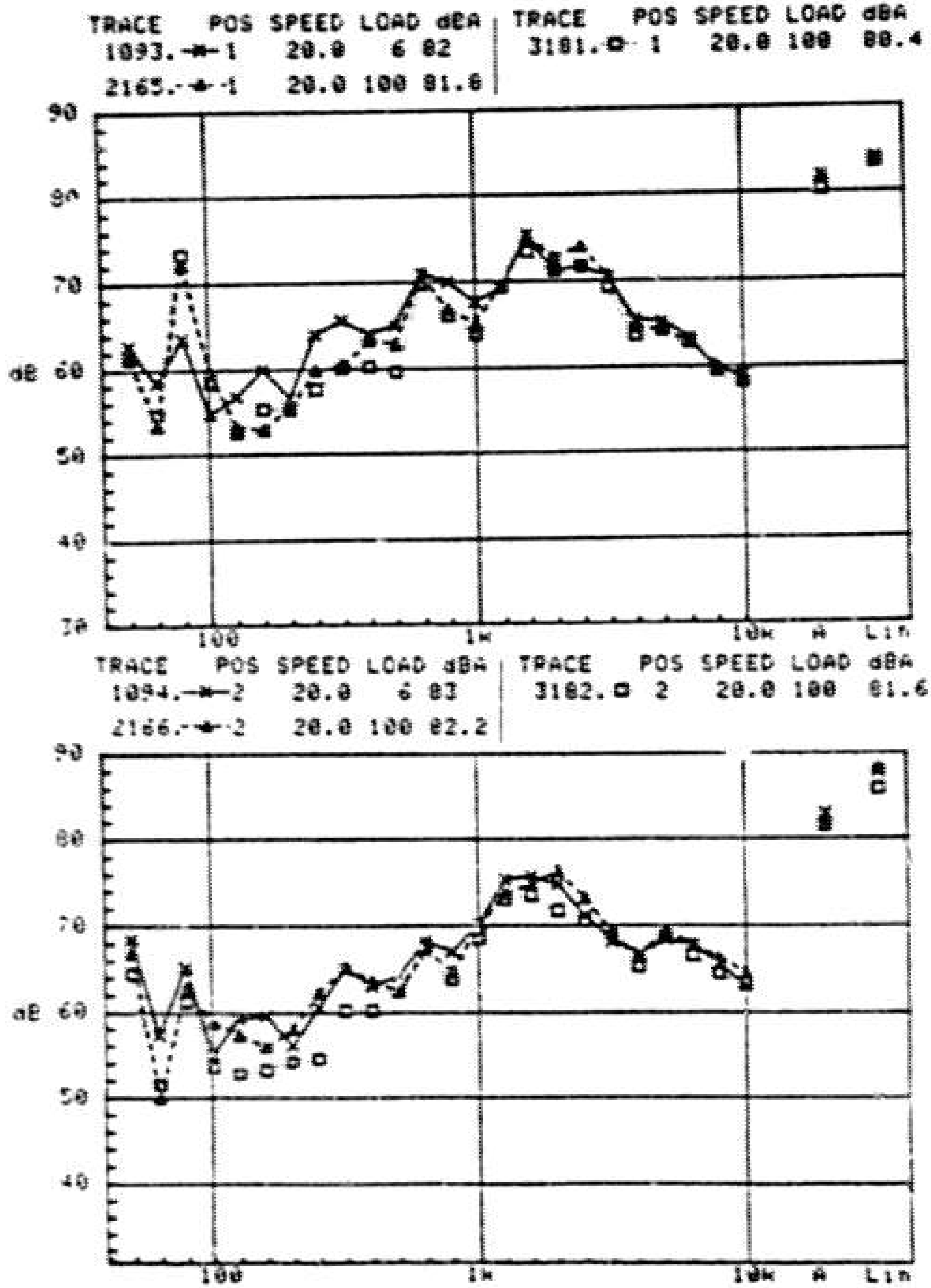


FIGURE 5-41. PEUGEOT XD2 EFFECT OF TIMING, FULL LOAD, 20 REV/S, MICROPHONE POSITIONS 1 AND 2

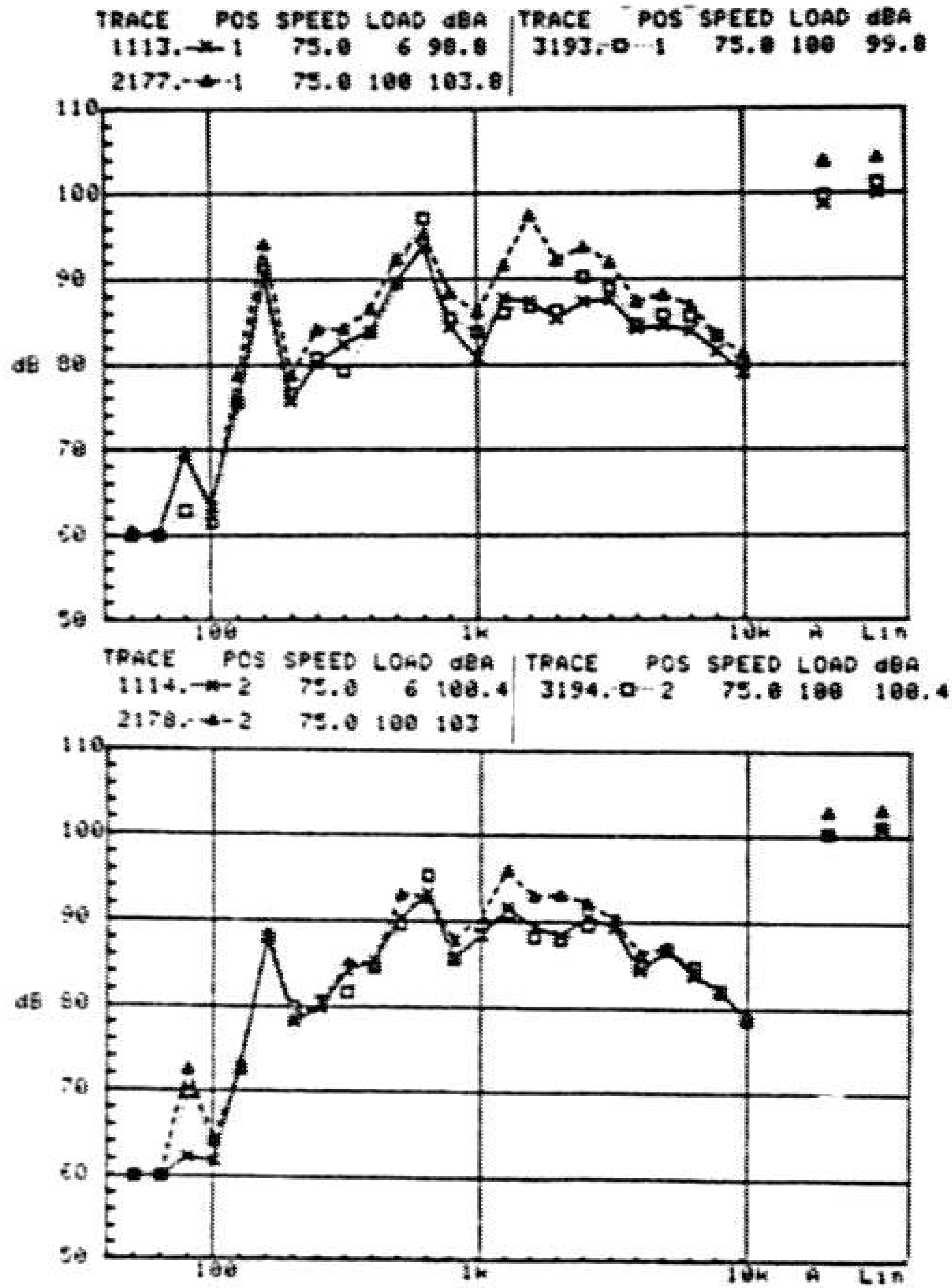


FIGURE 5-42. PEUGEOT XD2 EFFECT OF TIMING, FULL LOAD, 75 REV/S, MICROPHONE POSITIONS 1 AND 2

6. AN URBAN TRAFFIC NOISE MODEL FOR HIGH SPEED GASOLINE AND DIESEL POWERED LIGHT DUTY VEHICLES

6.1 INTRODUCTION

This letter report is one of a sequence of reports generated for the DOT, Transportation Systems Center, to evaluate the noise impact of small, internal combustion engines. The intent of this study is to obtain information on small, high speed engines so that their effect on the urban environment may be assessed and, if necessary, programs devised to reduce the noise from vehicles using these "highly desirable and more efficient power plants."

The objective of this phase of the study is to model the noise generated by small, high speed engine-powered vehicles in a low density, i.e., non-continuous source, urban environment to facilitate the evaluation of the noise impact of these types of vehicles. This modeling, to fulfill its original objectives, should utilize to as great an extent as possible the information the engine/vehicle data generated earlier in this program. Consequently, unlike most traffic noise models, the emphasis of this modeling will be on the engine/vehicle system as opposed to propagation/interaction effects.

6.2 GENERAL FORMULATION OF THE MODEL

Consistent with the above objectives, the sound pressure level due to a vehicle operating in an urban traffic environment $P^2(x)$ is assumed to be characterized by four elements. These four elements, shown schematically in Figure 6-1, are the engine, the engine/vehicle combination, vehicle operating characteristics in an urban traffic environment, and propagation interaction effects.

The first element $P^2(x)$, $F_1(x)$, describes the acoustic signature of the bare engine operating in a free field environment. The parameters x_1 which characterize this function are the

Engine

Engine/Vehicle

Vehicle Operation

Propagation/Interaction

$$P^2(x) = F_1 \otimes F_2 \otimes F_3 \otimes F_4$$

- Engine
  - o Combustion System/Fuel/Design Specifics
  - o RPM
  - o LOAD
  - o dRPM/dt, $\frac{d \text{ Load}}{dt}$
- Engine/Vehicle
  - o Cell/vehicle transfer function
  - o Vehicle design
  - o Engine accessories (fan, exhaust, intake)
  - o Vehicle sources (shell/panel radiation, tires)
- Vehicle Operation
  - o Utilization scenario
    i.e., RPM, LOAD, $\frac{d}{dt}$ (RPM, LOAD) as a function of time
- Propagation/Interaction
  - o basic R^{-N} propagation effects
  - o Interactive effects (multiple source/multiple scatter)

FIGURE 6-1. GENERALIZED MODEL

combustion system, fuel and other design characteristics as well as the RPM and Load (and their time derivatives) under which the engine is operating.

The second element in $P^2(x)$, $F_2(x)$, describes the modification of $F_1(x_1)$ by installation of the power plant in an operational vehicle as well as the additional sources characteristic of the vehicle itself. Some of the elements of F_2 are the free field/ vehicle transfer function, engine accessories (e.g., fan, exhaust system, etc.) and vehicle sources (e.g., panel radiation, tires, etc.).

The third element of $P^2(x)$, $F_3(x)$, characterizes the vehicle operation in an urban environment. That is, the utilization scenario, RPM, Load, d/dt(RPM), d/dt(Load) as a function of time in an urban environment.

Finally, the fourth element of $P^2(x)$, $F_4(x_4)$ characterizes the propagation and interaction effects of the basic signature (i.e., the first three elements) in an urban environment.

It should be noted at this point that these four elements of $P^2(x)$, $F_1(x_1)\ldots F_4(x_4)$, are coupled by the symbol $\circledast$. This symbol is used in its mathematical generality to denote a mathematical operation of which algebraic multiplication is only one possibility. Consequently, it does not necessarily mean that $P^2(x)$ can be characterized by the product of four functions, $F_1\ldots F_4$. Rather, the purpose of this generalized modeling is to delineate in a general sense the elements and phenomena which characterize $P^2(x)$ in a logical manner to assist in formulating an urban traffic model consistent with the original objectives and provide a framework to evaluate the completeness of the model.

6.3 MODELING OF VEHICLE OPERATION

Let us begin our modeling effort by looking at F_3, vehicle operation. Any impact model must in some way address vehicle operating conditions both for multi-source interaction (F_4) considerations as well as the speed-load dependence of the basic source.

This is especially important in urban environments where the operating cycle is such as to render simple approximations, e.g., a line source at a constant velocity, inappropriate. Consequently, this section of the modeling effort addresses the question of appropriate operating scenarios for this type of environment.

The detailed description of vehicle operating parameters (e.g., speed/load/vehicle separation) of a vehicle operating in an urban traffic situation is indeed complex. We will not attempt to quantify such detail beyond that needed for the task at hand.

As was noted earlier, this element of the modeling, F_3, addresses vehicle operating parameters in an urban environment. Primarily, then, we are looking to delineate how a vehicle (and thus the engine) is operated as a function of time in an urban traffic environment. This information is then used in conjunction with F_1, F_2 and F_4 to characterize $P^2(x)$.

6.3.1 General Approach

There are several ways of addressing this question. The approach to be taken should be dictated by the final use of the model. For example, we could set out to define in a statistical fashion how many vehicles in an urban environment are accelerating or decelerating, how many are operating in a steady state (constant velocity) mode, and how many are idling and what is the average time a typical vehicle spends in each of these modes. This type of an approach is appropriate to evaluate the collective noise radiated by a particular ensemble of vehicles.

We would also take the approach where we ask what are the typical operating parameters of a vehicle in an urban traffic environment. Then use this information, in conjunction with F_1, F_2 and F_4 to evaluate the acoustic signature of a particular vehicle being operated in a typical urban environment.

Since we are primarily interested in a modeling which will enable an evaluation of the impact of the introduction of particular types of vehicles into an urban environment, the second approach seems more useful in that it provides a framework whereby we can compare the acoustic effects of different vehicles operated in a similar manner representative of an urban traffic situation. Consequently, we will pursue the second approach to characterizing vehicle operation in an urban environment.

6.3.2 Characterization of Urban Vehicle Operation

In addition to the decision of individual as opposed to collective emphasis in the modeling, we must decide how we will model the vehicle operating characteristics. What we mean by that statement is that we can describe the vehicle operating characteristics from several different viewpoints. One approach could be to assume the design characteristics of a typical urban street, the number of lights or controls per mile, their cycle times, etc. With these assumptions and appropriate models for vehicle operations within such an environment, we could generate a typical urban operating cycle. We will call this a phenomenological model. We could take another approach, however. For example, we could treat the urban traffic network more or less as a "black box" ignoring the details such as street design parameters and traffic control systems and ask simply, "What percentage of times does a vehicle typically spend idling, accelerating, etc., in a representative urban network?" We call this a statistical approach. A median approach to the statistical modeling would be to use a "data-based" cycle such as the LA4 cycle and determine the statistical parameters we require directly. The following paragraphs discuss the complications and merits of each of these approaches.

6.3.2.1 Phenomenological Model - First, let us consider the phenomenological approach. We can divide an urban driving cycle into four components, consisting of the time spent 1) accelerating, 2) decelerating, 3) at steady-state cruise, and 4) idling. Let's look at the latter, first.

As a consequence of traffic controls, a typical vehicle spends a certain amount of time, t_i, idling at control points (e.g., traffic lights). This time, t_i, depends on several things, among them the:

- cycle time of traffic lights, i.e.,

  t_{red}, t_{green}, t_{amber}
- queue length at a given light
- number of lights in a given area.

This phenomenon is complex and has been studied by many investigators. A reasonably simple model for the delay at fixed time signals, given below, was proposed by Webster:

$$T_i = K\left\{\frac{t_{ci}(1 - \lambda_i)^2}{2(1 - \lambda_i x_i)} + \frac{x_i^2}{2Q(1 - x_i)}\right\}$$

t_c = cycle time (sec)

Q = vehicle flow (veh/sec/lane)

λ = portion of the cycle which is effectively green

= tg/tc

x = degree of saturation...the ratio of the flow to the maximum flow under the given signal settings

= $Q/\lambda s$

s = saturation flow (veh/sec/lane)

K = 0.90

The green time of the signal can also be modeled for a two-branch intersection in terms of the maximum flow in both branches such that:

$$t_g = c_o + c_1 x + c_2 x^4$$

where $c_o = 30$

$c_1 = 5x10^{-2}$

$c_2 = 2x10^{-10}$

$x = \max [\frac{Q}{N}|_{street\ 1} + \frac{Q}{N}|_{street\ 2} - 800]$

Q/N = vehicles/hour/lane

For simplicity, we can assume $t_{g1} = t_{g2}$. Thus, since

$$t_c = 2t_g + t_a$$

and $t_a = 2$, T_i is defined in terms of vehicle flow. The average idle time is thus given by

$$t_i = \sum_{j=i}^{N_c} T_i \left(\frac{Q}{N}|_i\right)$$

To determine or quantify in any detail the acceleration time or deceleration time involves considerable effort. For example, t_{accel} depends not only on traffic flow but queue length, in fact, the position of a given vehicle in the queue. Such an effort is outside the scope of this brief study. Consequently, we will approach this probelm from a very simple viewpoint. First assume that t_{accel} is equal to t_{decel}. Second, assume that a vehicle in the queue accelerates from stop to its cruise velocity at a constant acceleration. We know that the cruise velocity of a vehicle in traffic depends on the design velocity of the roadway, V_o, and the vehicle flow.

For urban traffic, studies have indicated that the cruise velocity can be modeled as a linear function such as:

$$V = V_o - K(\frac{Q}{N})$$

Consequently, with two earlier assumptions, the acceleration and deceleration time of each segment is given by:

$$t_{accel\ i} = t_{decel\ i} = \frac{Vi}{a} = \frac{V_{oi} - K(\frac{Q}{N})_i}{a}$$

and thus,

$$t_{accel} = t_{decel} = \sum_{i=1}^{Nc} 1 \frac{V_{oi} - K(\frac{Q}{N})_i}{a}$$

$$= \frac{1}{a} \sum_{i=i}^{Nc} 1 \ (V_{oi} - K(\frac{Q}{N})_i)$$

The remaining unknown is essentially determined by the previous development. For example, given a segment between controls of length L_i

$$t_{cruise\ i} = \frac{L_i - L_{accel}}{V_i}$$

But,

$$V_i^2 = 2a\ L_{accel\ i}$$

and

$$V_i = V_{oi} - K(\frac{Q}{N})_i$$

$$t_{cruise} = \sum_{i=i}^{Nc} \left[\frac{L_i}{V_{oi} - K(\frac{Q}{N})_i} - \frac{V_{oi} - K(\frac{Q}{N})_i}{a}\right]$$

Having defined the models for the four individual components of the urban drive cycle, the overall cycle is defined in terms of the parameters of these components, namely $(Q/N)_i$, max $(Q/N)_i$, s_i, V_{oi}, L_i, and a. But we can eliminate two of these parameters, max (Q/N) and s_i, by the following logic.

The max flow rate can be modeled in our velocity region of interest from the highway design manual which gives the maximum practical flow rate without controls as,

$$\max\left(\frac{Q}{N}\right) = 112 \frac{V_{oi(mph)}}{1 + 0.1\ V(mph)}$$

Similarly, an approximation to the saturation flow is given by,

$$S_i(veh/hr) \leq \frac{t_{gi}}{t_c}\left[\max\left(\frac{Q}{N}\right)_i\right]$$

Thus in this modeling of the urban vehicle operation, the relevant characteristics are specified by $(Q/N)_i$, V_{oi}, L_i and a.

6.3.2.2 Statistical Model - Now let us examine the second approach, the statistical approach. Several such models of this type have been developed over the years. We will discuss only one of the more recent models.

The model summarized here is a two-fluid approach to urban traffic. This model was developed by Herman and Prigogine.[1]

Kinetic theories of vehicular traffic have been developed over the past 20 years to attempt to describe the characteristics of traffic on multilane highways. This theory examines the evolution of the speed distribution function in terms of a number of important processes: the relaxation or speeding up process, which expresses the attempts of drivers to achieve their own desired speeds; the interaction or slowing down process, which arises in the conflict between a faster driver and a slower driver; and the adjustment process, which reduces the variance around the local mean speed. The details of all the vehicles in queues and the details of passing maneuvers are not addressed in this theory.

They analyzed a large amount of data in the form of speed-time histories of vehicles for many cities in the United States. The data were generated by following vehicles in each area studies, and they consist of speed-time histories and usage patterns of randomly selected vehicles operated under different traffic conditions as well as on various roadways. They have found that although the traffic in various areas is different, similar relations appear to exist between a number of traffic variables and the average speed. For example, the acceleration noise and the ratio of speed noise to average speed are correlated with average speed, and the stop time is linearly related to trip time, the reciprocal of average speed. These relations are surprisingly simple and global in character. For this reason they pursued an examination of the relation between trip time and stop time to see whether a theoretical basis could be developed for such seemingly general relations between some of the pertinent traffic variables.

The trip time on the links of a transportation network is a significant and useful variable for many facets of transportation engineering and planning. Travel time studies are often carried out to measure the effectiveness of a transportation system in terms of traffic engineering improvements and cost-benefit analyses. Trip time is perhaps the major factor in determining a driver's route choice and appears to be the most reliable single variable in the traffic assignment process.

Herman and Lam found that when the stop time was compared to the running time of the same trip in the Detroit suburban area, the stop time, for all practical purposes, varied linearly with the running time as well as with the total trip time. Similar results were obtained with two sets of previously reported data, one collected on a specific route in Berkeley, California, and the other collected on all the major arterial streets in Fresno, California. The slopes and intercepts obtained from linear fits of the data for stop time versus running time were reasonably consistent for the different data sets from different city areas.

The existence of a general trend in the data for trip time versus stop time suggested that there might be some underlying theoretical basis for such a result. This led them to consider a two-fluid model for traffic in towns.

The concept of a two-fluid model appeared in their earlier kinetic theory of multilane highway traffic when the transition to the so-called collective flow regime was achieved at sufficiently high vehicular concentrations. In this case the average speed depends on the fraction of the cars that are immobilized.

At the collective transition in the case of highway traffic, the velocity distribution for cars splits into two parts--one corresponding to moving vehicles and the other to vehicles that are stopped because of local conditions such as traffic jams. Likewise, the traffic in a network in a city may be considered to consist of two traffic fluids--one composed of moving cars and the other of cars that are stopped as a consequence of congestion, traffic signals, stop signs, and so on, but not in the parked condition. Parked cars are ignored as not being a component of the traffic: they form part of the street configuration. They assume that the average speed of the moving cars, v_r, depends on the fraction of cars that are moving. Thus, they might expect a relation of the form

$$v_r = v_m(1 - f_s)^n$$

where v_m is the average maximum running speed.

Noting that $v_m = 1/T_m$, where T_m is the average minimum trip time per unit distance, the trip time can be written as

$$T = T_r + T_s$$

where T_r and T_s are the running time per unit distance and the stop time per unit distance, respectively. In addition, it may be expected that

$$f_s = \frac{T_s}{T}$$

This statement can be considered as a type of ergodic condition relating ensemble averages to time averages. There is then the implication that the fraction of the time stopped for a vehicle circulating in the network is equal to the average fraction of stopped cars in the system over the same period. If the overall concentration varies widely -- that is, fluctuates rapidly during the time of the trip -- this condition may not be satisfied. The concentration must vary slowly over the time during which T_s/T and f_s are measured.

We can write:

$$v_r = \frac{1}{T_m} (1 - f_s)^n$$

Since by definition

$$v = v_r f_r$$

then

$$v = \frac{1}{T} = \frac{1}{T_m} (1 - f_s)^n f_r = \frac{1}{T_m}(1 - f_s)^{n + 1}$$

or

$$\frac{T_m}{T} = (1 - f_s)^{n + 1}$$

Since $f_s = T_s/T$, we have

$$1 - \frac{T_s}{T} = \left(\frac{T_m}{T}\right)^{\frac{1}{n+1}}$$

and finally

$$T_s = T - T_m^{\frac{1}{n+1}} T^{\frac{n}{n+1}}$$

An urban network in this theory is characterized by the (T_m, n) pair of values. In Figure 6-2 from their paper, they show a plot of T versus T_s in units of minutes per mile. The quantity T_m is taken as 2 min/mile, corresponding to an average maximum speed of 30 miles per hour. Three curves are given for n = 1, 2, and 3. The curvature is small in all cases, so that they essentially have a linear relation between the trip time and the stop time. Furthermore, the curve for n = 2 corresponds fairly well to the general overall trend of the data given in Figure 6-2. They have not attempted to fine-tune the functional representation by adjusting T_m and n because they were seeking mainly the character of the overall trend.

The reasonableness of the assumption that the average speed of the moving vehicles depends on the fraction of the vehicles that are moving has been shown above. The question now arises whether we can go further in our attempt to describe traffic in towns. Unfortunately, this theory is not easily adapted to the needs of this modeling in that it is difficult to accommodate the acceleration/deceleration modes within the framework we have developed to describe the vehicle noise/operating condition relationship. This theory is useful, however, as a guide to formulating the noise model developed in this study. We will come back to this point later in this text.

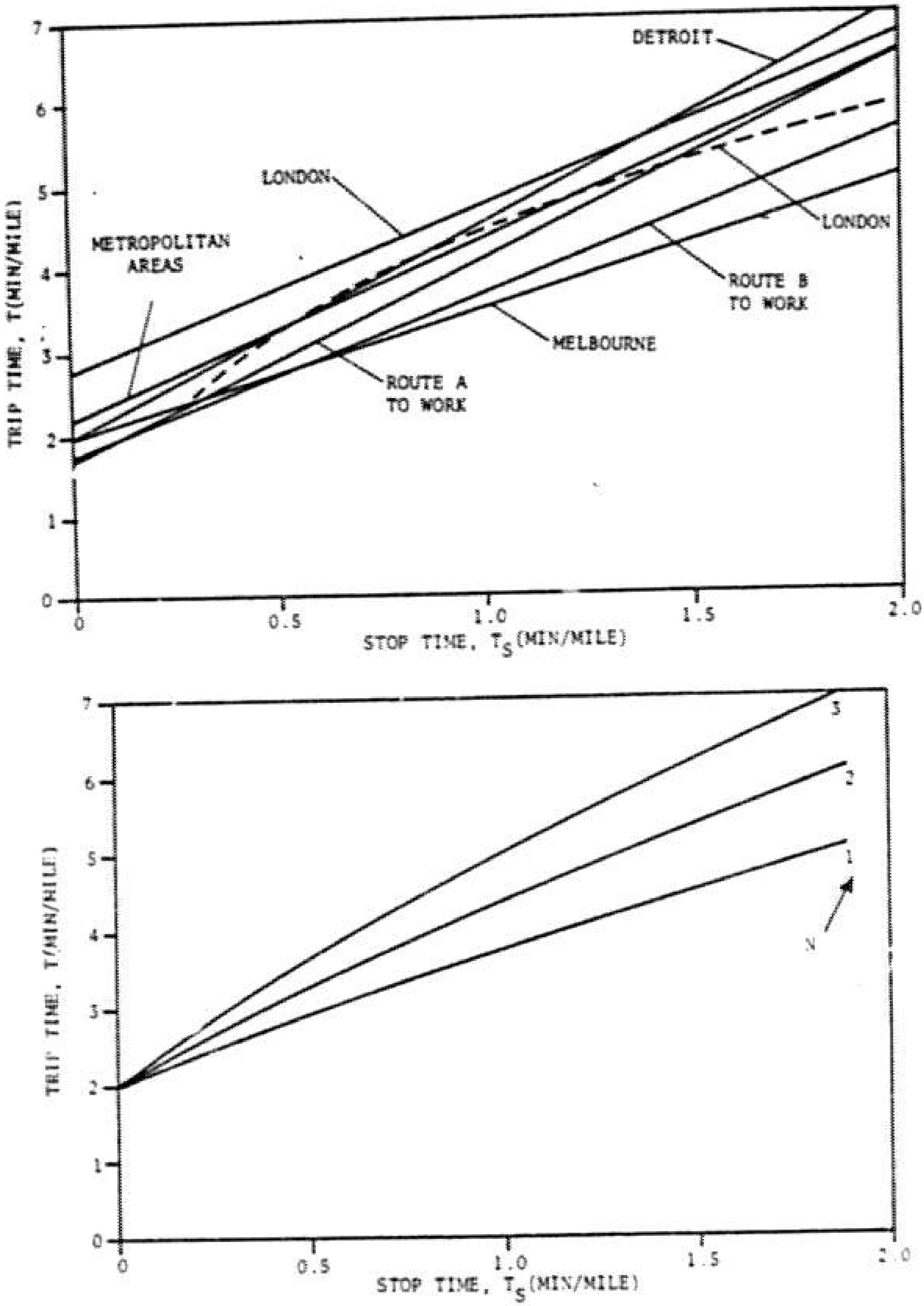


FIGURE 6-2. TRIP TIME VS STOP TIME

6.3.2.3 Model Based on Existing Urban Vehicle Cycle - A third way of characterizing urban vehicle operational characteristics is to synthesize a distribution function for the various operating modes from the data of a velocity time history of an existing urban cycle such as the LA4 cycle. The fidelity of the statistics so generated depends on several things. The first of these is how representative the data are of a typical urban cycle. Considering that LA4 cycle is the standard CVS emissions cycle, we will assume that the "representativeness" of the data has been justified. The second question affecting the statistics is the length of the overall cycle and the number of cycles contained within the overall cycle and the data reduction technique used to generate the distribution function.

Due to time and cost constraints, the statistics discussed here were acquired by a judgemental "eyeball" fit into the four time categories discussed earlier: accelerating, decelerating, idle, and cruise. The data so acquired should be adequate for the purposes of this modeling but by no means should be taken as statistically definitive of the LA4 cycle.

The statistics of this "approximated LA4 cycle" are described in Table 6-1. It can be seen from this figure that the statistics generated from this approximated LA4 cycle are somewhat coarse; however, they should be adequate for our needs.

The idle statistics are reasonable with the exception of the number of events in the 9-12 range, since we would expect the statistics to be roughly Poisson due to the queueing effect at signals (assuming a random arrival of vehicles). The acceleration statistics are probably describable by the summation of two distributional functions. The range $0 - 5.5 \times 10^{-2}$ g's brings acceleration events from stop or low velocity. The deceleration statistics are basically uniform across the range from $1.5 - 14 \times 10^{-2}$ g's. The velocity statistics look roughly gaussian with a mean representative of a velocity around the average speed limit in an urban/suburban area ~ 30 mph.

TABLE 6-1. APPROXIMATE STATISTICS OF THE LA4 CYCLE

EVENT							
IDLE		ACCELERATION		DECELERATION		CRUISE	
Time (Sec)	# Events	g's x 10^{-2}	# Events	g's x 10^{-2}	# Events	Speed (mph)	# Events
0 - 4	1	1.5 - 2.8	5	1.5 - 2.8	1	0 - 6	0
5 - 8	4	2.9 - 4.2	3	2.9 - 4.2	2	7 - 12	2
9 - 12	1	4.3 - 5.6	2	4.3 - 5.6	4	13 - 18	2
13 - 16	4	5.7 - 7.0	4	5.7 - 7.0	3	19 - 24	8
17 - 20	2	7.1 - 8.4	6	7.1 - 8.4	1	25 - 30	14
21 - 24	1	8.5 - 9.8	5	8.5 - 9.8	2	31 - 36	4
25 - 28	1	9.9 - 11.2	1	9.9 - 11.2	5	37 - 42	0
29 - 32	1	11.3 - 12.6	4	11.3 - 12.6	4	43 - 48	1
33 - 36	0	12.7 - 14.0	1	12.7 - 14.0	3	49 - 54	2
37 - 40	1	14.1 - 15.4	1	14.1 - 15.4	4	55 - 60	2
# Cycles	16	32		28		35	
T_{event}/T_{tot} (%)	17.8	25.1		20.5		36.6	

Of the three models we have discussed, the phenomenological model, the statistical model, and the existing cycle-based model, the latter appears to offer the best compromise between applicability to the needs of the present noise modeling and adaptability of the formulation within the cost and time constraints of the present project. The physical modeling insights provided by the first two models do prove to be of value in configuring the overall model approach, however. Consequently, this approach appears reasonable and viable for describing typical urban vehicle operation, and we will use this approximated LA4 cycle, shown in Table 6-4, in the final model.

6.4 MODELING OF ENGINE/VEHICLE ACOUSTIC SIGNATURE

Having established the manner in which we will describe vehicle operation in an urban environment, we now can move on to the next aspect of the modeling which is $F_1 \circledast F_2$, the engine and engine/vehicle characteristics as a function of the operational parameters of our modified LA4 cycle model.

During the program we gathered controlled parametric data on the engine/vehicle system (i.e., $F_1 \circledast F_2$) which is of sufficient detail to meet the needs of this modeling. We will therefore model the product function $F_1 \circledast F_2$.

To refersh our memory, as was discussed in Section 6-2, $F_1 \circledast F_2$ describes the radiated acoustic field of the engine and vehicle in a given operational mode. In this section of the report we will discuss methods of quantifying the magnitude of this radiated field. The four operational modes for which we want to quantify the radiated acoustic field are idle, acceleration, steady state cruise and deceleration.

6.4.1 Idle Noise

Of these four modes, the first, idle noise, is straightfoward both in concept and measurement. During this program idle noise levels were measured on a multitude of vehicles. The results are summarized in Table 6-2.

TABLE 6-2. SUMMARY OF IDLE NOISE LEVELS FOR DIESEL AND GASOLINE VEHICLES (3M FROM FRONT OF VEHICLE)

Vehicle	Sound Pressure Level (dBA)
DIESEL POWERED VEHICLES	
Opel 2100D (OD)	63.0
Opel 2100D TURBOCHARGED (OTD)	63.5
Peugeot 504 GLD (P)	64.5
Mercedes 240D	64.5
Oldsmobile Delta 88	65.5
VW Golf LD	63.0
GASOLINE POWERED VEHICLES	
Plymouth Volare	57.5
Rover 3500	58.3
Dodge Aspen	58.0
Dolomite Sprint (DS)	53.5
Jaguar XJ6 (J)	57.0
Saab 99 GL (Fan off) (S)	58.5
Volvo 244 GL (V)	59.5
Cortina 1600 (CT)	57.5
Ford Fiesta (Fan off) (F)	56.0
Alpine S (Fan off) (A)	59.0
Chevette GL (CV)	50.5
Renault 4 (R)	48.0

Two things are evident in this data base. First, the idle noise levels of diesel powered vehicles exceeds that of gasoline powered vehicles by some 4-5 dBA. Second, transverse mounted engine vehicles (Chevette GL and Renault 4) are considerably quieter than longitudinal mounted engine vehicles even with the fan off. Table 6-2 then presents the data that we will use as representative of the idle mode of operation.

6.4.2 Steady-State Cruise Noise

Next we will consider the acoustic signature representative of the steady state mode of operation. Figure 6-3 summarizes the steady state ($\frac{dv}{dt} = 0$) sound pressure level at 7.5 m from the vehicle (in this case, the Saab 99) as a function of engine speed and gear. Consistent with our original framework discussed in Section 6-2., we can think of this steady-state signature as having two components. The first component is the noise of the rolling vehicle (drive train noise, panel radiation, tire noise, etc.). The other component is the noise of the engine and accessories as installed in the vehicle. We will take as representative of the first component the correlation shown in Figure 6-4. This correlation was derived from the data acquired when the vehicle was coasting by the microphone array with the engine off. We will call this L_{CB}(dBA) for coast-by.

This data gives the correlation

$$L_{CB} = 32 \log RPM + 32 \log K_2 - 73.9 \text{ (dBA)}$$

where $K_2 = V/(RPM/1000)$.

The other component, the noise of the engine and accessories as installed in the vehicle, we will model in the following manner. Assume that when the vehicle is operated in its lowest gear, i.e., first gear, that this data is representative of the engine/accessory signature L_e (dBA). In the case of the Saab vehicle (Figure 6-3) the first gear data is modeled by the correlation

$$L_e = 49 \log RPM - 103 \text{ (dBA)}.$$

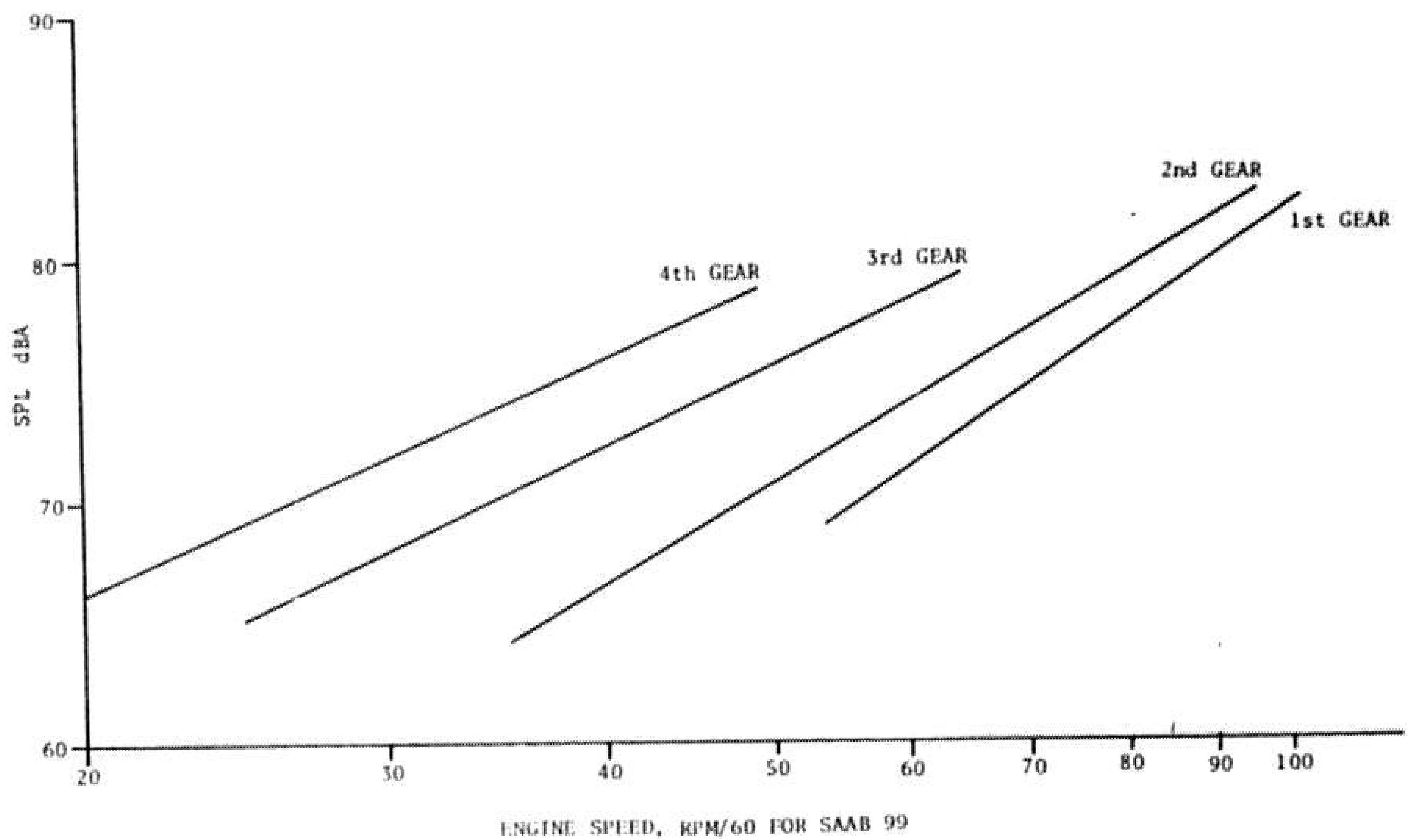


FIGURE 6-3. STEADY-STATE SOUND PRESSURE LEVEL AS A FUNCTION OF GEAR FOR THE SAAB 99 VEHICLE

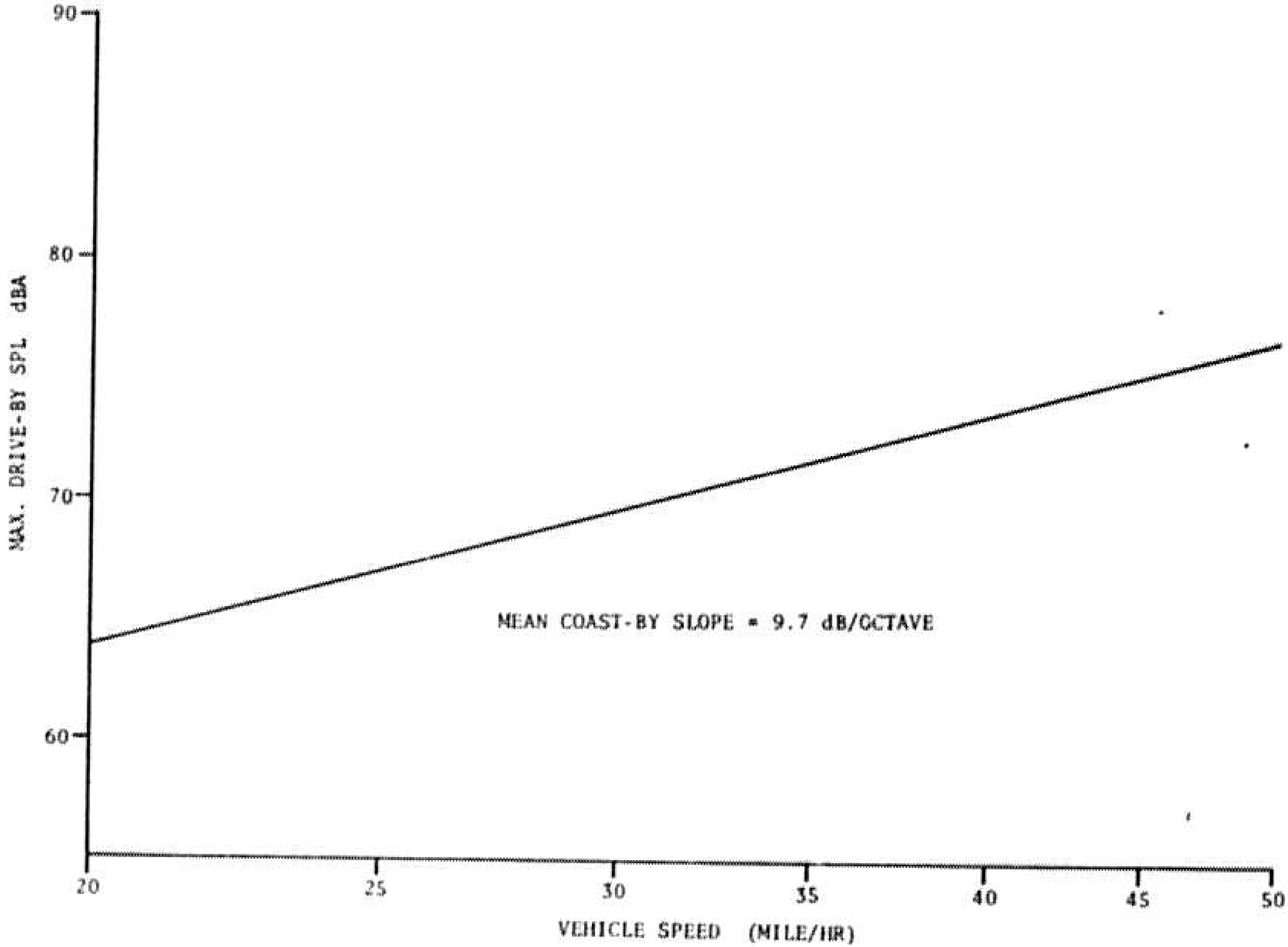


FIGURE 6-4. COAST-BY SOUND PRESSURE LEVEL

Similarly, the Peugeot data[2] is modeled by

$$L_e = 45.9 \log RPM - 84 \text{ (dBA)}.$$

It is interesting to note that both of these correlations are close to the classical engine noise prediction formulae given below, which lends some credibility to our assumption that the first gear data are representative of the engine/accessory signature.

$$L_e'(\text{gasoline}) = 50 \log RPM - K_1$$

$$L_e'(\text{naturally aspirated IDI}) = 43 \log RPM - K_2.$$

The comparison of the model to the measured data for both vehicles is shown in Figures 6-5 and 6-6. The correlation with the Saab data is very good, while the correlation with the Peugeot data is reasonable (especially for RPM/60 > 30), and acceptable for our purposes.

It should be noted, however, that these were derived from engine test cell data, i.e., F_1 type, not vehicle data. Having described both L_e and L_{CB} steady state operation level or cruise level, L_{cruise} is given by

$$L_{CR} = 10\log_{10}(10^{L_e/10} + 10^{L_{CB}/10}) \text{ (dBA)} \qquad (6\text{-}4\text{-}1)$$

In general then, the model that we will use for the acoustic cruise signature is given by,

$$L_{CR}(\text{dBA}) = 10 \log_{10}(10^{K_{11}\log RPM/10 + K_{12}/10} + 10^{K_{21}\log RPM/10 + K_{22}/10}) \qquad (6\text{-}4\text{-}2)$$

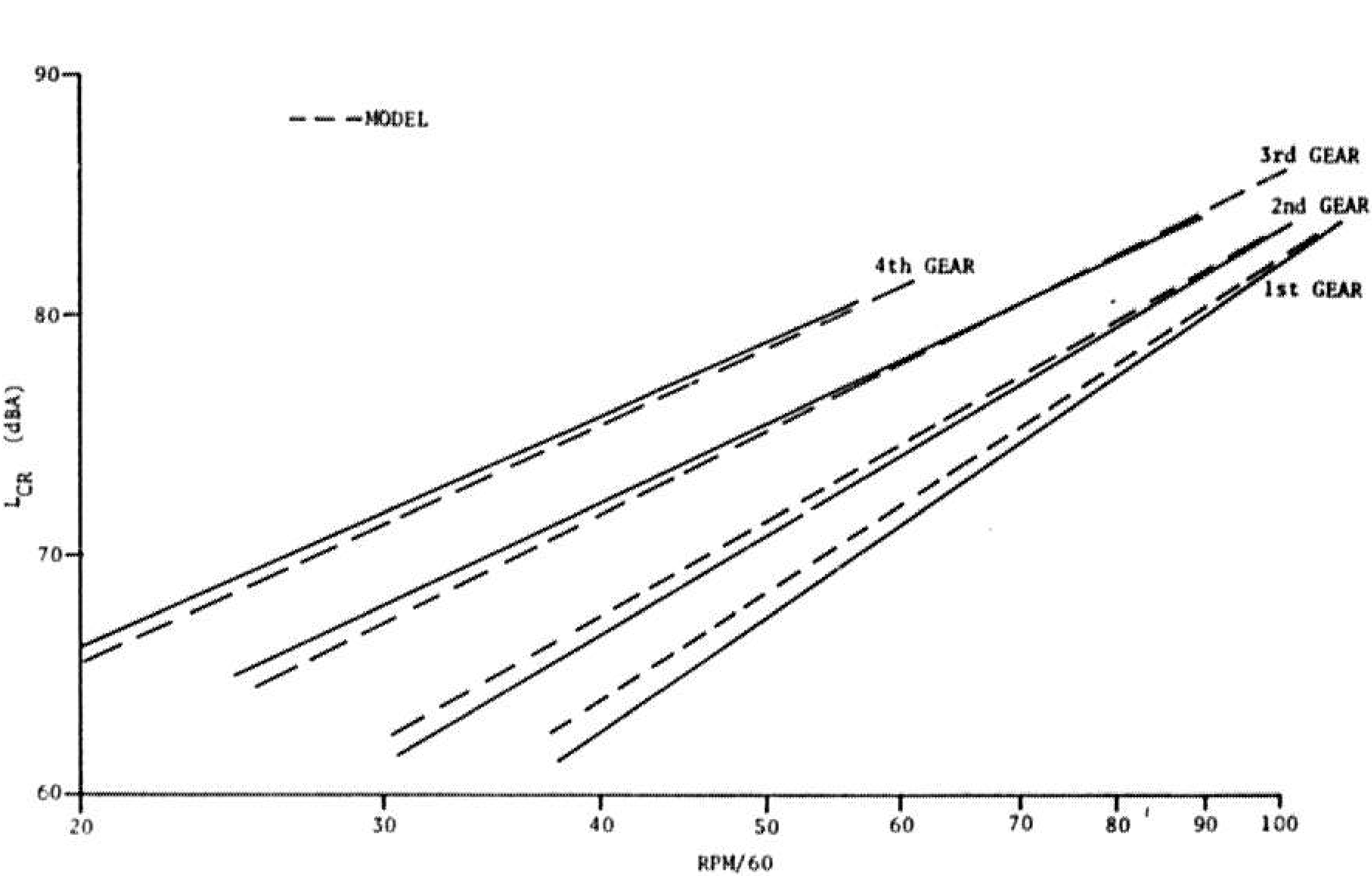


FIGURE 6-5. COMPARISON OF MODEL WITH STEADY STATE DATA ON SAAB 99

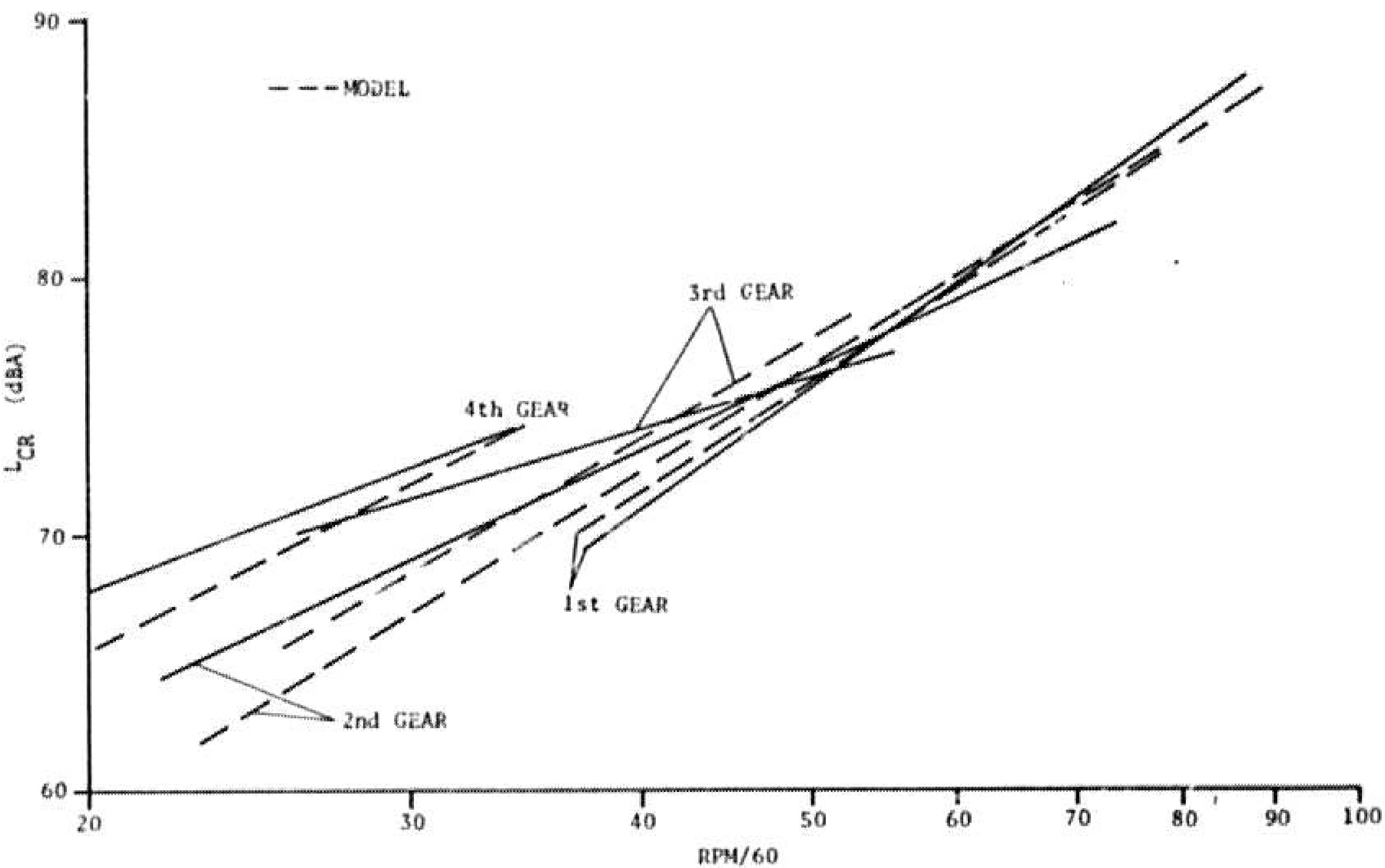


FIGURE 6-6. COMPARISON OF MODEL WITH STEADY STATE DATA ON PEUGEOT 50 GLD

6.4.3 Acceleration and Deceleration Noise

Two more signatures remain to be defined; they are the signature for the acceleration mode and the signature for the deceleration mode.

We will discuss first the deceleration signature. Little, if any, data appears to be available to model the acoustic signature of a vehicle in this operational mode. However, we can approximate the deceleration mode signature by the following logic. In this mode of operation, certainly we will have a contribution from the vehicle and tires similar to the radiation from a coast-by. We will assume for the lack of a better approximation that this contribution is equal to the coast-by level. Next we will have a contribution from the engine as modified by the vehicle. Now in a deceleration mode of operation, the combustion process will have a small contribution due to the very nature of the deceleration process. However, studies performed on the Saab and Peugeot engines during this program show that both of these engines are mechanically dominated as opposed to combustion dominated. Consequently, if we take these engine characteristics to be representative and typical, then we could take the engine contribution during deceleration to be less than or equal to but similar to the steady-state passby levels for a given engine speed. Consequently, given these two results, we will assume the deceleration level to be modeled by the steady state cruise level in a high gear, which we will choose arbitrarily to be third gear.

Now, we must model the remaining mode of operation, the acceleration mode. This mode is perhaps the most difficult to model because of the inherent complications of transient engine operating conditions, varying acceleration rates, etc., all of which can influence the radiated acoustic signature.

There are several existing test procedures such as the SAE J386b and ISO which are standardized acceleration mode acoustic test procedures. Data were gathered earlier in this program which may assist us in indicating whether such single number descriptors, as provided by these test procedures, are appropriate for this modeling. During the course of this program, the acoustic signatures of two vehicles being operated under ISO conditions as well as several constant acceleration rates were acquired. These data are discussed in detail in the RICARDO report DP77/1158, and the results are summarized in Figures 6-7 and 6-8. These tests showed that there is an effect of acceleration rate on the radiated noise level, but by no means is the effect linear or necessarily consistent at different engine RPM. However, in general as the vehicle acceleration increases from 0 (steady state), the radiated noise level increases. Thus, Figures 6-7 and 6-8 show the envelope of minimum and maximum levels measured from these acceleration tests. The lower trace for a given gear is the steady state of cruise-by level. It can be seen from these figures that the Saab data shows considerably more variation with acceleration than does the Peugeot data. This is primarily due to exhaust resonance. Such effects are difficult at best to model.

However, we can model the maximum SPL data for both vehicles, shown in Figures 6-9 and 6-10, and find the correlations.

$$\text{Max Saab}_L\ (\text{dBA}) = 25.75 \log_{10} \text{RPM} - 13.25$$

$$\text{Max Peugeot}_L\ (\text{dBA}) = 33.2 \log_{10} \text{RPM} - 37.3$$

Thus in the acceleration mode L_{acc} at a given RPM can be bounded by:

$$\text{Saab}_{L_{CR}} \leq \text{Saab}_{L_{acc}}(\text{dBA}) \leq \text{Max Saab}_L$$

$$\text{Peugeot}_{L_{CR}} \leq \text{Peugeot}_{L_{acc}}(\text{dBA}) \leq \text{Max Peugeot}_L$$

A close examination of the magnitude of these bounds is not warranted due to the nature of the approximations that went into them. The magnitude of the difference is instructive in the case

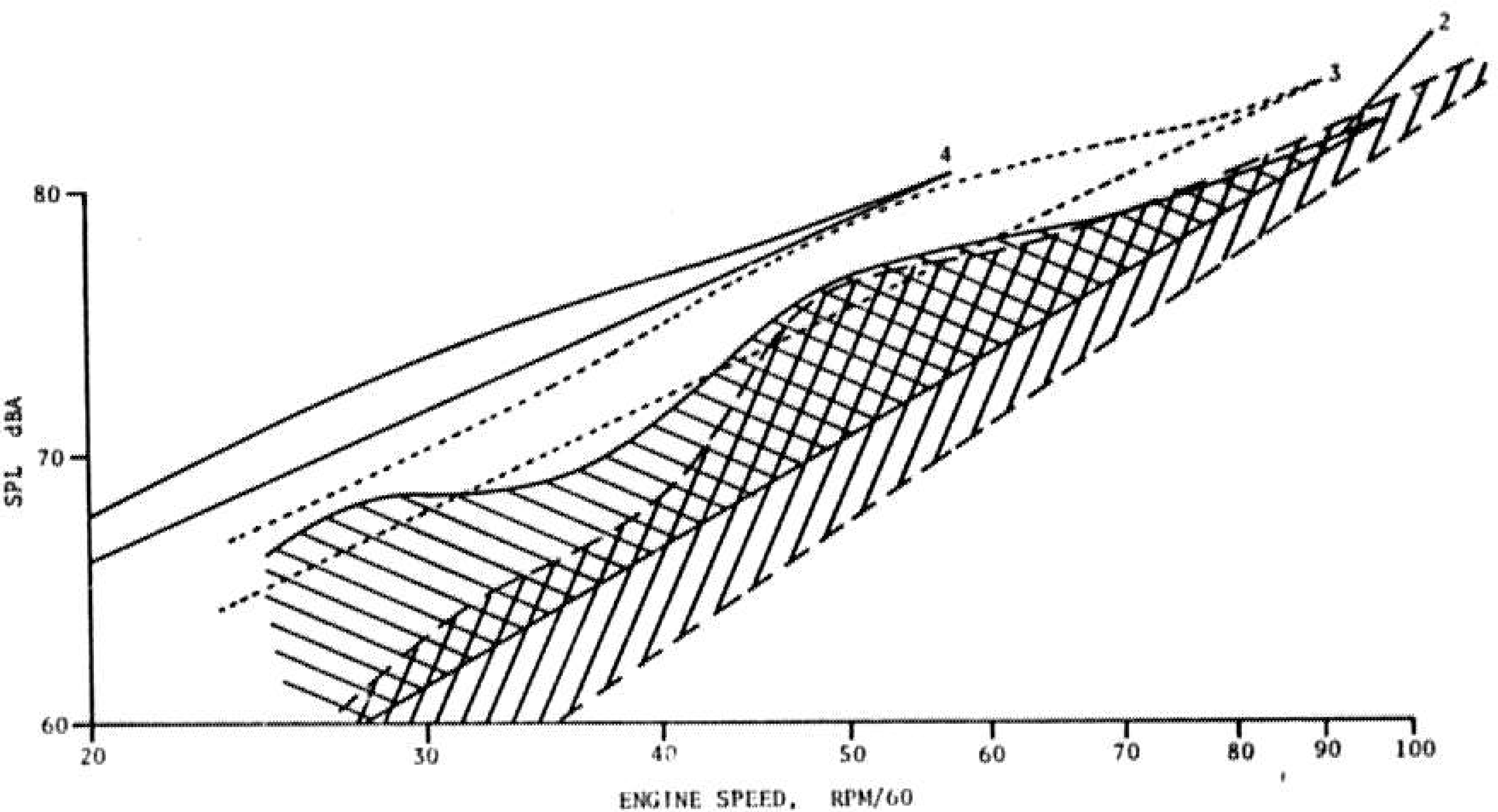


FIGURE 6-7. ENVELOPES OF THE SOUND PRESSURE LEVEL MEASURED AS A FUNCTION OF GEAR AT VARIOUS CONSTANT ACCELERATION RATES FOR THE SAAB 99 VEHICLE

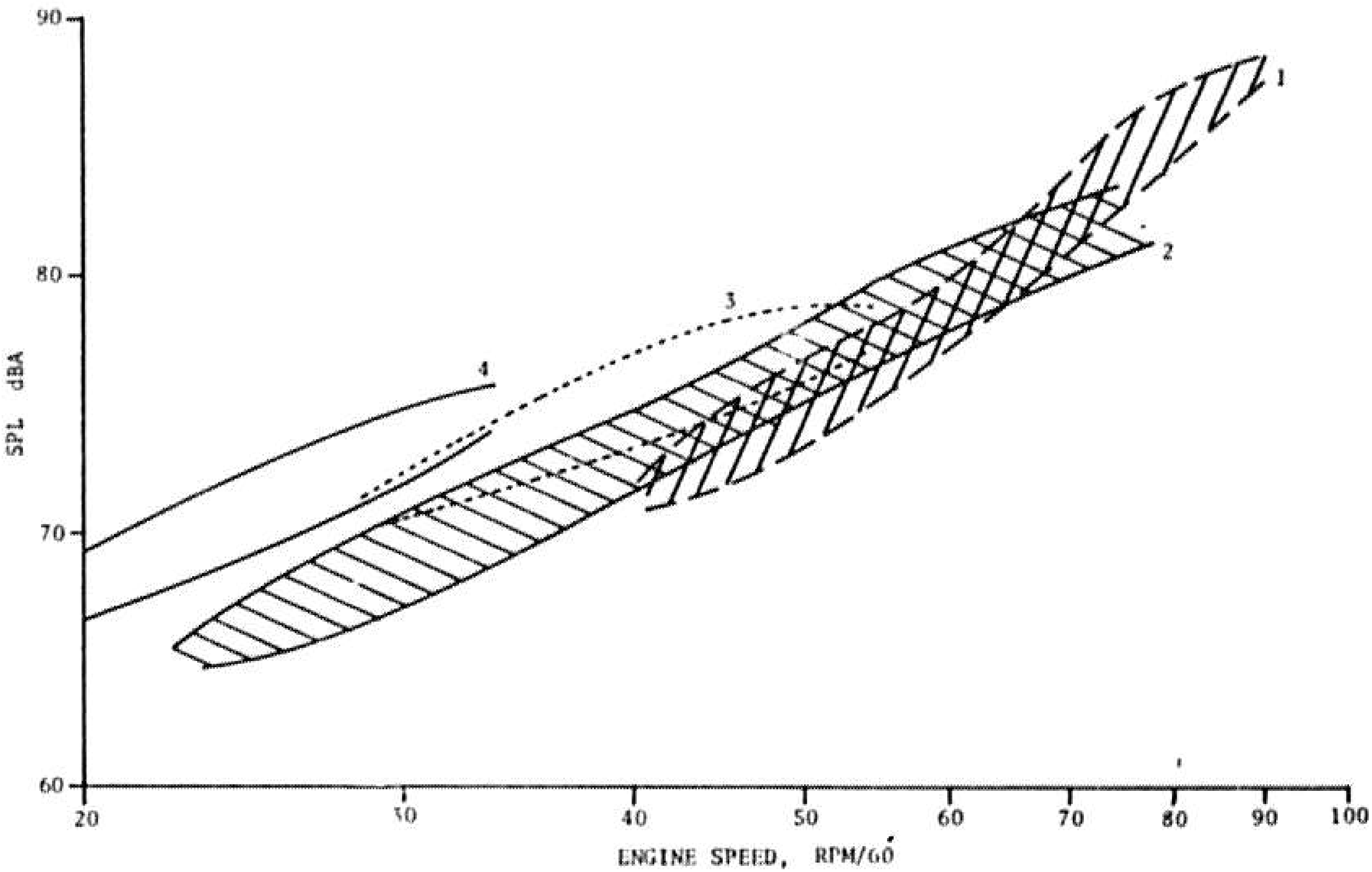


FIGURE 6-8. ENVELOPES OF THE SOUND PRESSURE LEVEL MEASURED AS A FUNCTION OF GEAR AT VARIOUS CONSTANT ACCELERATION RATES FOR THE PEUGEOT 504 GLD VEHICLE

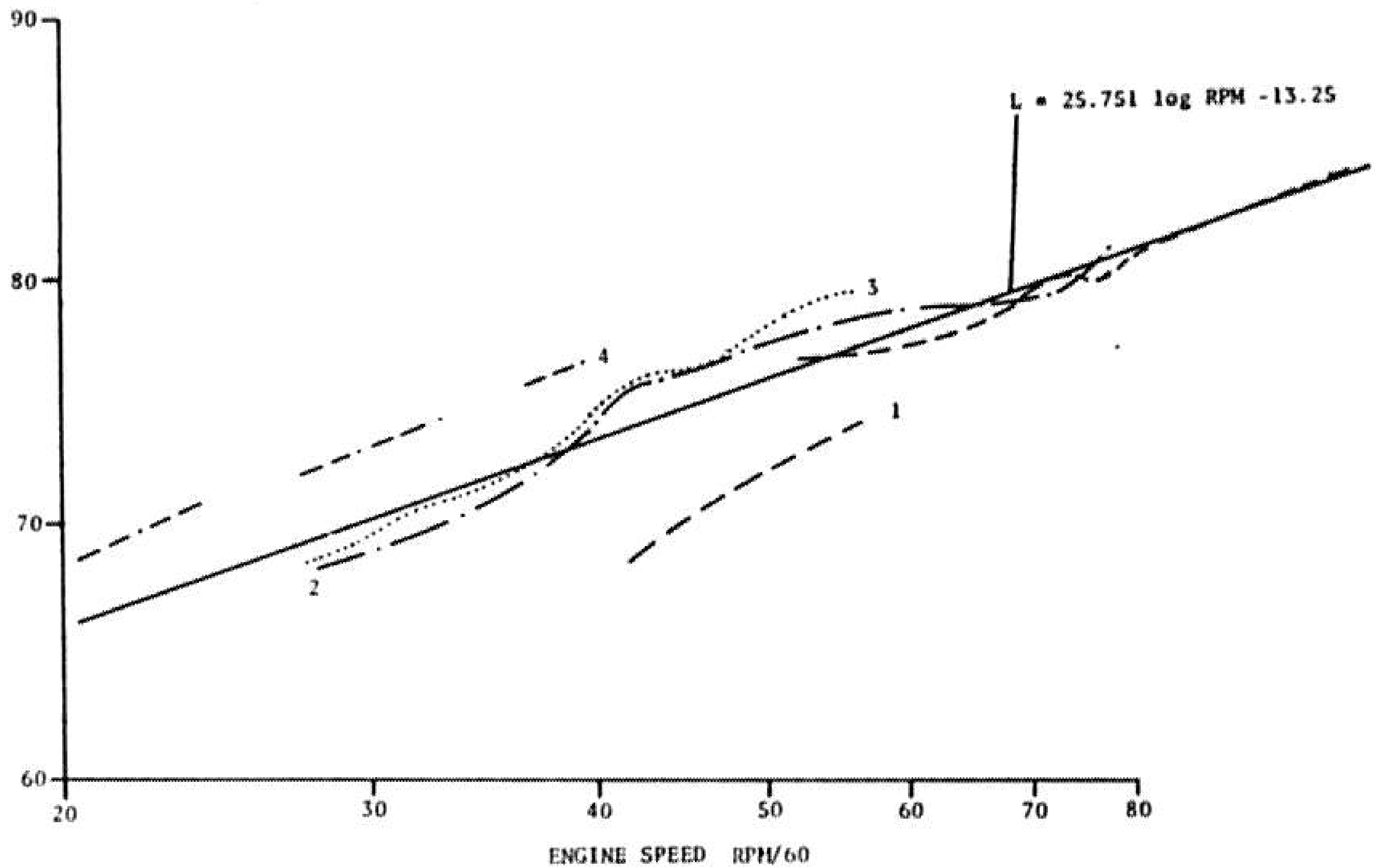


FIGURE 6-9. APPROXIMATE MAXIMUM LEVELS (SAAB) UNDER ACCELERATION

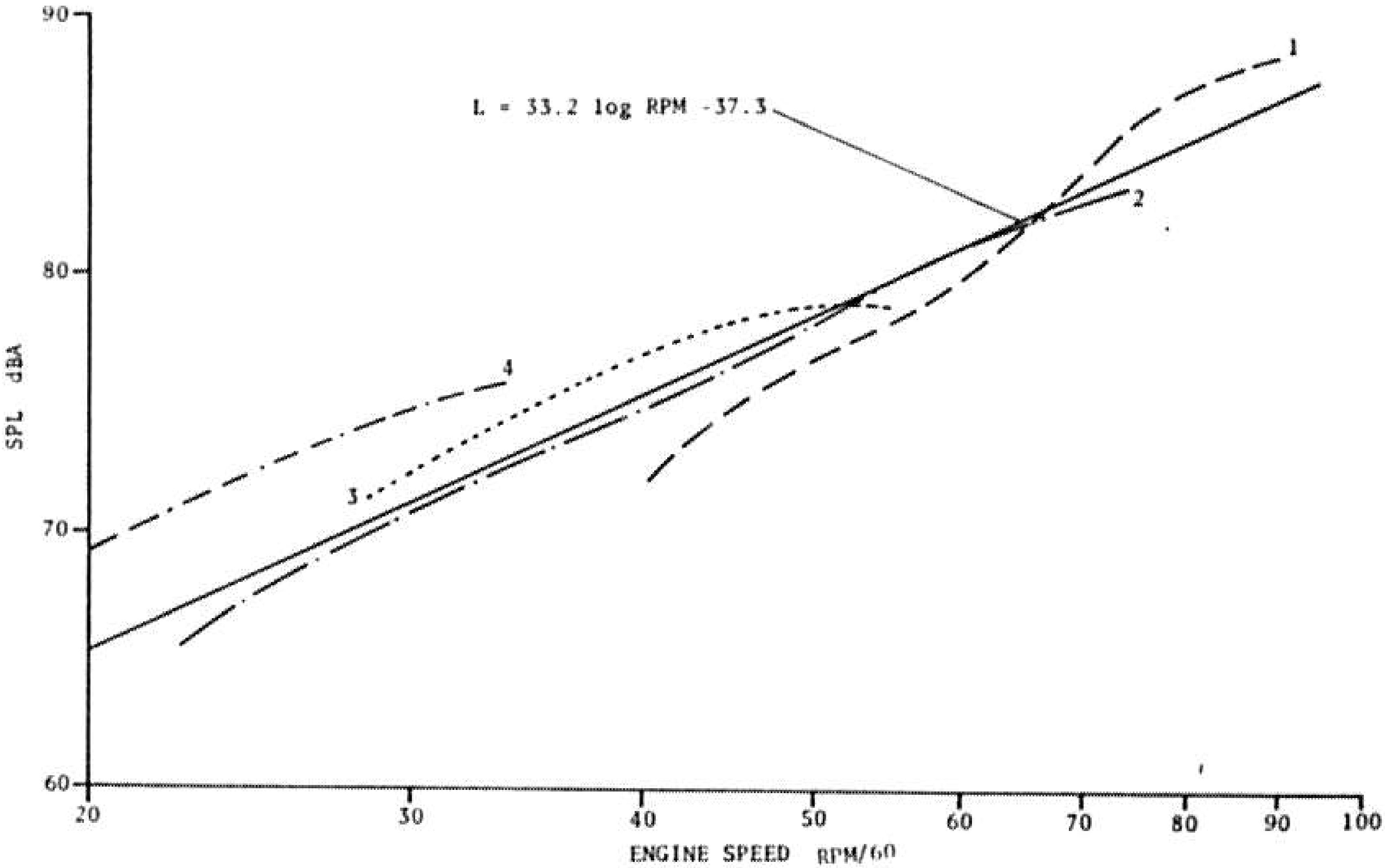


FIGURE 6-10. APPROXIMATE MAXIMUM LEVELS (PEUGEOT) UNDER ACCELERATION

of the Saab, especially (see Figure 6-5) in that it points out how details of design in vehicles (in this case the exhaust system) can vary significantly from vehicle to vehicle.

To get an idea as to how these models approximate the acceleration mode, we have compared the ISO "max" ISO test results of some 10 vehicles with the correlation

$$L = 25.75 \log RPM - 13.25 \equiv \alpha_1 \log RPM + \alpha_2 \qquad (6\text{-}4\text{-}3)$$

The data and this correlation are shown in Figure 6-11.

The RPM used here is the engine speed at the midpoint of the test course. The ISO test is the ISOR362 procedure while the "max" ISO test is the same procedure with the exception that the entry speed has been raised so that the engine reaches rated RPM at the test zone exit. This test is felt to maximize the engine noise contribution to the ISO signature.

It can be seen that this simple correlation is reasonable across this fairly large spectrum of vehicles. True, the spread is plus or minus some 2.5 dB; however, given the variance possible (e.g., Figure 6-7 Saab) and the spectrum of vehicles, the correlation is felt to be reasonable. Consequently, we will use the form of equation 6-4-3 as indicative of the sound pressure level of an accelerating vehicle.

This then completes the modeling of the function $F_1 \circledast F_2$ for all of the operating modes of F_3. This leaves us then with only F_4 (propagation/interaction) to model. We will do little in this area for two reasons: (1) the propagation/interaction problem is difficult and outside the scope of this program, and (2) the objective of this modeling is to effect an evaluation of relative, not absolute, acoustic impact. Consequently, since it does not compromise the objectives of this study, we will define $F_4 = 1$. We have now

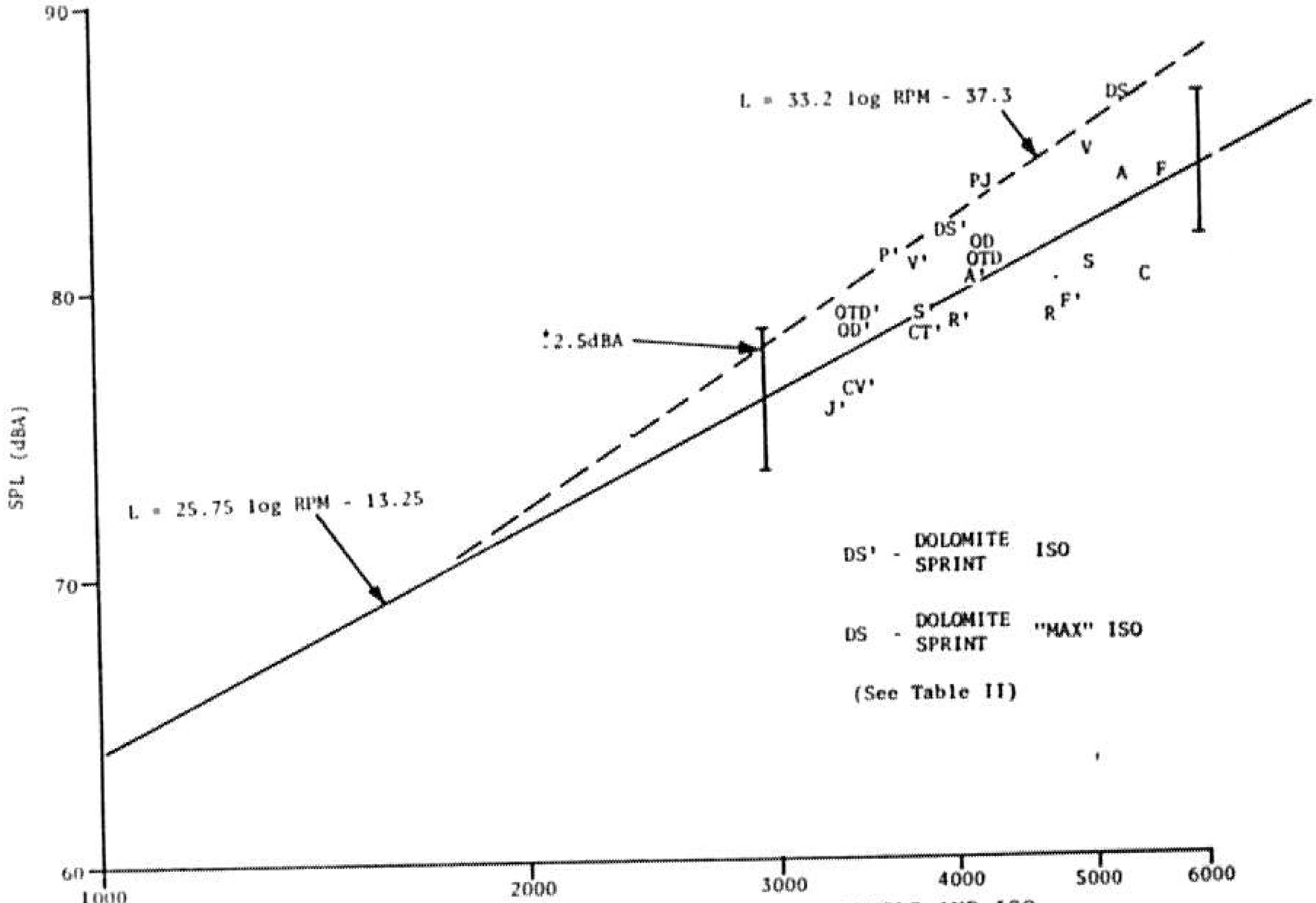


FIGURE 6-11. FIT TO APPROXIMATE MAXIMUM LEVELS AND ISO

fulfilled our original objective which was to model the sound pressure level of a vehicle operating in an urban environment, using as much new information from other facets of this program as possible.

6.5 MODELING THE ACOUSTIC IMPACT

At this stage, one problem remains, which is, what is the appropriate measure to estimate the acoustic impact, knowing the sound pressure level? Consider the following argument. First, we are interested in the relative impact, not per se absolute impact, the latter being the more difficult task. Secondly, the impact will vary depending on the observers location. For example, let's consider a "typical" city block. Statistically, an observer standing or living at an intersection will experience considerably more idling noise levels than will an observer living in the middle of a long city block who statistically, again, will experience more steady-state cruise noise levels than either idling or acceleration levels. An observer mid-way between our other two hypothetical observers will experience on the average acceleration levels and/or cruise levels depending on many things, among them the traffic density and average speed. It seems then that a global type statistic would be appropriate; for lack of any better, we will use L_{eq}.

$$L_{eq}(\Delta t) = 10 \log_{10} \left[\frac{1}{\Delta t} \int_{to}^{to + \Delta t} p^2(t)dt\right]$$

if we let Δt be a "typical" cycle which we defined earlier. Next, in order to fully define $p^2(t)$, we must fix our observer somewhere. We could fix a propagation constant of $p(t) = {}^{Po(t)}/_{Dk(t)}$ and integrate over some time period, or we could assume that our hypothetical observer could be anywhere in the block with equal probability and on the average is some distance D away from a vehicle. The latter seems as reasonable as the former and is mathematically much simpler to implement. Thus, we will adopt the latter. Consequently, L_{eq} becomes

$$L_{eq}(\Delta t) = 10\log_{10}[\frac{1}{\Delta t}\ \{\int_{t_o}^{t_o + t_{idle}} p^2(t)dt + \int_{t_o + t_i}^{t_o + t_i + t_{accel(t)}} p^2(t)dt\ -$$

$$+ \int_{t_o + t_i + t_{a+}}^{t_o + t_i + t_a + t_{cruise}} p^2(t)dt + \int_{t_o + t_i + t_a + t_c}^{t_o + t_i + t_a + t_c + t_{a(-)}} p^2(t)dt\ ]\ \}]$$

where $t = t_{idle} + t_{accel(+)} = t_{cruise} + t_{accel(-)} \equiv t_{cycle}$.

Now, $p^2{}_{idle}(t)$ is independent of time, consequently, for a given vehicle.

$$\int_{t_o}^{t_o + t_{idle}} p^2{}_{idle}(t)dt = p^2{}_{idle}\ T_{idle}$$

The values of $p^2{}_{idle}$ for different vehicles are listed in Table 6-2.

Similarly the integral,

$$\int_{T_{cruise}} p^2{}_{cruise}(t)dt$$

is readily integrated since $p^2{}_{cruise}$ is independent of time being given earlier by

$$p^2{}_{cruise} = \sum_{j=1}^{2} 10^{(K_{1j}\ \log RPM\ -\ K_{2j})/10} = \sum_{j=1}^{2} 10^{-K_{2j}/10}(RPM)^{K_{1j}/10}$$

Since $V_{cruise} = K_{cg}(RPM)$

$$\int_{T_{cruise}} p^2_{cruise}\, dt = \sum_{j=1}^{2} \sum_{i=1}^{Nc} 10^{-K_{2j}/10} \left[\frac{V_{ci}}{K_{cgi}}\right]^{K_{1j}/10} t_{cri}$$

$$= \sum_{j=1}^{2} 10^{-K_{2j}/10} \sum_{i=1}^{Nc} \left(\frac{V_{ci}}{K_{cgi}}\right)^{K_{1j}/10} t_{cri}$$

The remaining two integrals are slightly more difficult for various reasons. First, let us use a general form of the acceleration sound pressure level that we found earlier, i.e.,

$$p^2_{accel}(t) = 10^{(\alpha_1 \log RPM(t) - \alpha_2)10} = 10^{-\alpha_2/10} (RPM(t)^{\alpha_1/10})$$

In the acceleration mode the RPM is not independent of time as in the cruise case, thus

$$\int_{T_{accel}} p^2_{accel}(t)dt = \sum_{i=1}^{Nc} \int_{t_{ai}} 10^{-\alpha_2/10} (RPM(t))^{\alpha_1/10} dt$$

$$= \sum_{i=1}^{Na} 10^{-\alpha_2/10} \int_{t_{ei}}^{t_{ui}} (RPM(t))^{\alpha_1/10} dt$$

$$= 10^{-\alpha_2/10} \sum_{i=1}^{Na} \int_{t_{ei}}^{t_{up}} \left(\frac{V}{K_{ag}}\right)^{\alpha_1/10} dt$$

Since $V = at$, $dv = adt$ if $a = const$

$$\int_{T_{accel}} p^2_{accel}(t)dt = 10^{-\alpha_2/10} \sum_{i=1}^{Na} \frac{1}{a_{ai}} \int_{V_{ei}}^{V_{ai}} \left(\frac{V}{K_{ag}}\right)^{\alpha_1/10} dV$$

This would seem to be a straightforward integration. However, it is complicated by the fact that depending on the velocity, K_{ag} is in fact not a constant. Thus more correctly this integral should be written:

$$\int_{V_{ei}}^{V_{ai}} \left(\frac{V}{K_{ag}}\right)^{\alpha_1/10} dV = \int_{V_{ei}}^{V_{ui}} \left(\frac{V}{K_{ag}(V)}\right)^{\alpha_i/10} dV$$

To facilitate this integration, let us consider the following: for each gear there will be a given operational RPM range. For example, in first gear

$$RPM_{L1} \leq RPM_{\text{first gear}} \leq RPM_{u1}$$

where RPM_{u1} is the chosen first gear shift point. Thus, the velocity range of first gear will be

$$K_{ag1}(RPM_{L1}) \leq V_1 \leq K_{ag1} RPM_{u1}$$

Similar relations hold for the other gears, and in general

$$K_{agi}(RPM_{Li}) \leq V_K \leq K_{agi}(RPM_{ui})$$

Thus, we could write a general expression for $K_{ag}(V)$ in the following manner.

$$\frac{1}{K_{ag}(V)} = \sum_{i=1}^{Ng} \frac{1}{K_{agi}} S(K_{agi} RPM_{ui}, K_{agi} RPM_{Li})$$

where $S(x,y) = 1$ if $K_{agi} RPM_{Vi} \leq V \leq K_{agi} RPM_{Li}$

$= 0$ otherwise

We must be careful here, however, to assure that the integration is continuous, i.e., to assure that we do not integrate over more than one gear for a given velocity. We can do this by adjusting the RPM limits, i.e.,

$$K_{ag1}\ RPM_{u1} = K_{ag2}\ RPM_{L2}$$

which defines RPM_{L2}, i.e.,

$$RPM_{L2} = [\frac{K_{ag1}}{K_{ag2}}]\ RPM_{u1}$$

Similarly,

$$K_{ag2} RPM_{u2} = K_{ag3} RPM_{L3}$$

$$K_{ag3} RPM_{u3} = K_{ag4} RPM_{L4}$$

Thus, the limits of integration become

Lower Limit	Upper Limit
RPM_{L1} (definition)	RPM_{u1} (definition)
$RPM_{L2} = [\frac{K_{ag1}}{K_{ag2}}]\ RPM_{u1}$	RPM_{u2}
$RPM_{L3} = [\frac{K_{ag2}}{K_{ag3}}]\ RPM_{u2}$	RPM_{u3}
$RPM_{L4} = [\frac{K_{ag3}}{K_{ag4}}]\ RPM_{u3}$	RPM_{u4}

We can further simplify things by making the shift RPM in all gears the same, i.e.,

$$RPM_{ui} = R_s \quad \text{for all } i$$

Thus all limits are defined by the gear ratios of the vehicle and two RPM's, $RPM_{L1} = R_o$ and R_s. Thus we can write our expression for $K_{ag(V)}$ by the following,

$$\frac{1}{K_{ag(V)}} = \frac{1}{K_{ag1}} S(K_{ag1}R_s, K_{ag1}R_o)$$

$$+ \frac{1}{K_{agi}} S(K_{agi}R_s, K_{ag(i-1)}R_s)$$

where s(x,y) is defined on page 35.

Furthermore, since S is binary $S(x,y)^{1/10} = S(x,y)$

$$\int_{V_{Li}}^{V_{ui}} \left(\frac{V}{K_{ag(V)}}\right)^{\alpha_1/10} dv = \sum_{j=1}^{Ng} (K_{agi})^{\frac{-\alpha_1}{10}} S_i \left.\frac{V^{\frac{\alpha_1}{10}+1}}{\frac{\alpha_1}{10}+1}\right|_{V_{Li}}^{V_{ui}}$$

Thus finally,

$$\int_{T_{accel}} P^2_{accel}(t)dt = 10^{-\alpha_2/10} \sum_{i=1}^{Na} \frac{1}{a_{ai}} \sum_{J=1}^{Ng} (K_{agj})^{\frac{-\alpha_1}{10}} S_i \left.\frac{V^{\frac{\alpha_1}{10}+1}}{\frac{\alpha_1}{10}+1}\right|_{V_{Li}}^{V_{ui}}$$

Where a_i, V_{ui} and V_{Li} are defined by the approximated LA4 cycle and α_1, α_2 by the earlier fit to the acceleration data (K_{agi} are defined by the choice of vehicle gearing). The remaining integral to be evaluated is

$$\int_{T_{decel}} P^2_{decel}(t)dt$$

Now, $P^2_{decel}(t)$ was given earlier as describable by

$$P^2_{decel}(t) = P^2_{cruise}(t) = \sum_{j=1}^{2} 10^{-K_{2j}/10} (RPM(t))^{K_{1j}/10}$$

Now in this case to simplify the integration, we will assume (not unrealistically) that the driver does not downshift upon deceleration but stays in a given gear. Thus,

$$P^2_{decel}(t) = \sum_{j=1}^{2} 10^{-K_{2j}/10} \left(\frac{V}{K_{dg}}\right)^{K_{1j}/10}$$

and consequently,

$$\int_{T_{decel}} P^2_{decel}(t)dt = \sum_{j=1}^{2} \sum_{i=i}^{Nd} \frac{1}{a_{di}} \int_{V_{ui}}^{V_{ui}} 10^{-K_{2j}/10} \left(\frac{1}{K_{dg}}\right)^{K_{1j}/10} dV$$

$$= \sum_{j=1}^{2} \sum_{i=i}^{Nd} \frac{1}{a_{di}} 10^{-K_{2j}/10} K_{dg}^{-K_{1j}/10} \left. \frac{V^{\frac{K_{1j}}{10}+1}}{\frac{K_{1j}}{10}+1} \right|_{V_{Li}}^{V_{ui}}$$

Thus, L_{eq} is uniquely defined as follows:

$$L_{eq} = 10 \log_{10} \left(\frac{1}{T_{tot}} \sum_{i=i}^{4} X_i\right)$$

where

$$X_1 = P^2_{idle}\, T_{idle} \qquad (6\text{-}5\text{-}1)$$

$$X_2 = \sum_{j=1}^{2} \sum_{k=1}^{Nc} 10^{-K_{2j}/10} \left(\frac{Vck}{K_{cgk}}\right)^{K_{1j}/10} t_{crk} \qquad (6\text{-}5\text{-}2)$$

$$X_3 = 10^{-\alpha_2/10} \sum_{i=1}^{Na} \sum_{j=1}^{Ng} \frac{1}{a_{ai}} (K_{agj})^{-\alpha_1/10} S_j \left. \frac{V^{\alpha_1/10+1}}{\frac{\alpha_1}{10}+1} \right|_{V_{Li}}^{V_{ui}} \qquad (6\text{-}5\text{-}3)$$

$$X_4 = \sum_{j=1}^{2} \sum_{i=1}^{Nd} \frac{1}{a_{di}} 10^{-K_{2j}/10} (K_{dg})^{-K_{1j}/10} \left. \frac{V^{K_{1j}/10+1}}{\frac{K_{1j}}{10}+1} \right|_{V_{Li}}^{V_{ui}} \qquad (6\text{-}5\text{-}4)$$

$$T_{tot} = T_{idle} + T_{cr} + T_{accel} + T_{decel} \qquad (6\text{-}5\text{-}5)$$

where

$$T_{\alpha} = \sum_{K}^{Nd} t_{dk}$$

Equations 6-5-1 through 6-5-6, whose parameters are discussed in Table 6-4, describe the acoustic impact of a high-speed-engined vehicle operating in an urban environment. The model is unambiguous and readily evaluated by simple digital techniques. Unfortunately, time and funding constraints do not permit the coasting and exercize of this model. However, all of the elements necessary to exercize the model are given in this report, and it should be a straightforward task to effect such an evaluation.

6.6 DISCUSSION

Some generalizations from the model are possible without a detailed evaluation. If we look at how L_{eq} will vary from vehicle to vehicle, we see that the value of X_1 will depend directly on the value of the idle sound pressure level P^2_{idle} since T_{idle} will be the same for all vehicles. In X_2 if we assume grossly that all the vehicles to be evaluated are about the same weight, then three parameters will vary from vehicle to vehicle. These are K_{11}, K_{12} and K_{cgk}, the engine contribution to the cruise signature and the gearing respectively. The only parameter to vary from vehicle to vehicle will be K_{agj}, the gearing. While X_4 has a sensitivi.y to vehicle parameters similar to that of X_2, consequently it is evident from this simple analysis that the gearing of the vehicle, as well as combustion system, will have an effect on the acoustic impact as modeled in this paper. If one were to evaluate the acoustic effect of changing gearing while leaving the power plant fixed, care must be taken to assure that the acceleration rates required to drive the cycle can be achieved.

This model affords considerable flexibility for parametric evaluation (e.g., gearing, shift points, etc.). It should always be remembered, however, that gearing is chosen for a given vehicle and power plant to provide a given performance level, but if vehicle flexibility, fuel economy or emission. Consequently, if the effect of gearing on the acoustic impact is to be evaluated, care should be taken to note the effects of such a change on these performance parameters.

TABLE 6-3. L4A CYCLE

Time (sec)	mph
0.5	[illegible]
1.5	[illegible]
2.5	[illegible]
3.5	[illegible]
4.5	[illegible]
5.5	[illegible]
6.5	[illegible]
7.5	[illegible]
8.5	[illegible]
9.5	[illegible]
10.5	[illegible]
11.5	[illegible]
12.5	[illegible]
13.5	[illegible]
14.5	[illegible]
15.5	[illegible]
16.5	[illegible]
17.5	[illegible]
18.5	[illegible]
19.5	[illegible]
20.5	1.5
21.5	4.5
22.5	7.3
23.5	[illegible]
24.5	12.9
25.5	15.[illegible]
26.5	17.1
27.5	17.7
28.5	19.[illegible]
29.5	21.2
30.5	22.1
31.5	22.4
32.5	22.3
33.5	21.8
34.5	21.2
35.5	20.7
36.5	[illegible]
37.5	18.4
38.5	[illegible]
39.5	[illegible]
40.5	15.[illegible]
41.5	15.3
42.5	15.8
43.5	18.8
44.5	18.1
45.5	20.1
46.5	21.4
47.5	22.8
48.5	22.8
49.5	22.7
50.5	23.4
51.5	20.1
52.5	18.1
53.5	15.5
54.5	15.8
55.5	15.8
56.5	14.7
57.5	20.7

Time (sec)	mph
58.5	22.4
59.5	23.7
60.5	24.4
61.5	24.8
62.5	24.9
63.5	24.8
64.5	24.5
65.5	24.5
66.5	24.7
67.5	24.8
68.5	24.7
69.5	24.8
70.5	24.9
71.5	25.4
72.5	25.7
73.5	25.8
74.5	25.2
75.5	24.9
76.5	25.2
77.5	25.7
78.5	26.0
79.5	25.9
80.5	25.9
81.5	26.4
82.5	27.1
83.5	28.1
84.5	29.0
85.5	29.8
86.5	30.3
87.5	30.3
88.5	33.8
89.5	30.7
90.5	30.8
91.5	30.5
92.5	30.4
93.5	30.4
94.5	30.8
95.5	30.9
96.5	30.7
97.5	26.7
98.5	29.7
99.5	30.1
100.5	30.5
101.5	30.8
102.5	30.6
103.5	30.0
104.5	30.7
105.5	32.1
106.5	29.9
107.5	30.1
108.5	30.5
109.5	31.0
110.5	31.5
111.5	32.0
112.5	32.3
113.5	32.3
114.5	32.0
115.5	30.2
116.5	26.9
117.5	23.7
118.5	20.4
119.5	17.1
120.5	13.7

Time (sec)	mph
121.5	10.4
122.5	7.1
123.5	4.9
124.5	1.1
125.5	[illegible]
126.5	[illegible]
127.5	[illegible]
128.5	[illegible]
129.5	[illegible]
130.5	[illegible]
131.5	[illegible]
132.5	[illegible]
133.5	[illegible]
134.5	[illegible]
135.5	[illegible]
136.5	[illegible]
137.5	[illegible]
138.5	[illegible]
139.5	[illegible]
140.5	[illegible]
141.5	[illegible]
142.5	[illegible]
143.5	[illegible]
144.5	[illegible]
145.5	[illegible]
146.5	[illegible]
147.5	[illegible]
148.5	[illegible]
149.5	[illegible]
150.5	[illegible]
151.5	[illegible]
152.5	[illegible]
153.5	[illegible]
154.5	[illegible]
155.5	[illegible]
156.5	[illegible]
157.5	[illegible]
158.5	[illegible]
159.5	[illegible]
160.5	[illegible]
161.5	[illegible]
162.5	[illegible]
163.5	1.8
164.5	4.9
165.5	8.3
166.5	11.8
167.5	14.9
168.5	18.1
169.5	21.0
170.5	23.3
171.5	25.1
172.5	26.1
173.5	28.1
174.5	25.4
175.5	24.9
176.5	24.9
177.5	25.1
178.5	25.3
179.5	25.8
180.5	26.5
181.5	26.9
182.5	25.2
183.5	23.4

Time (sec)	mph
184.5	21.1
185.5	18.8
186.5	17.5
187.5	17.7
188.5	18.4
189.5	19.3
190.5	21.1
191.5	23.4
192.5	25.8
193.5	28.5
194.5	31.1
195.5	33.7
196.5	36.1
197.5	38.3
198.5	39.6
199.5	41.3
200.5	42.8
201.5	44.3
202.5	45.8
203.5	46.4
204.5	47.1
205.5	47.5
206.5	47.4
207.5	47.3
208.5	47.1
209.5	47.6
210.5	47.[illegible]
211.5	47.6
212.5	47.6
213.5	47.1
214.5	47.3
215.5	47.7
216.5	48.2
217.5	48.8
218.5	49.3
219.5	49.8
220.5	50.3
221.5	50.8
222.5	51.2
223.5	51.9
224.5	52.7
225.5	53.7
226.5	54.4
227.5	54.7
228.5	54.9
229.5	54.9
230.5	54.7
231.5	54.0
232.5	54.7
233.5	54.6
234.5	55.3
235.5	55.8
236.5	55.6
237.5	56.2
238.5	56.4
239.5	56.7
240.5	56.7
241.5	56.8
242.5	56.8

Time (sec)	mph
243.5	56.5
244.5	55.5
245.5	56.5
246.5	56.5
247.5	56.4
248.5	56.2
249.5	55.9
250.5	55.4
251.5	54.9
252.5	54.4
253.5	54.1
254.5	53.9
255.5	53.7
256.5	53.8
257.5	54.0
258.5	54.1
259.5	54.1
260.5	53.9
261.5	53.6
262.5	53.2
263.5	52.8
264.5	52.4
265.5	52.2
266.5	52.2
267.5	52.0
268.5	51.8
269.5	51.6
270.5	51.6
271.5	51.7
272.5	52.0
273.5	52.3
274.5	52.7
275.5	53.2
276.5	53.8
277.5	54.3
278.5	55.2
279.5	55.5
280.5	55.8
281.5	56.0
282.5	55.9
283.5	55.5
284.5	54.9
285.5	54.0
286.5	53.1
287.5	52.4
288.5	51.5
289.5	51.5
290.5	51.3
291.5	50.5
292.5	50.4
293.5	50.1
294.5	50.0
295.5	49.8
296.5	49.6
297.5	49.5
298.5	49.5
299.5	49.3
300.5	48.9
301.5	48.4
302.5	47.7
303.5	46.7
304.5	45.6
305.5	44.4

TABLE 6-3. L4A CYCLE (CONTINUED)

Time (sec)	mph	Time (sec)	mph	Time (sec)	mph	Time (sec)	mph	Time (sec)	mph
306.5	43.7	369.5	34.8	•		495.5	26.7	558.5	0.0
307.5	42.1	370.5	35.1	432.5	0.0	496.5	24.0	559.5	0.0
308.5	40.9	371.5	35.7	433.5	0.0	497.5	21.7	560.5	0.0
309.5	39.4	372.5	36.4	434.5	0.0	498.5	18.2	561.5	0.0
310.5	37.7	373.5	36.0	435.5	0.0	499.5	14.9	562.5	0.0
311.5	36.1	374.5	36.0	436.5	0.0	500.5	11.7	563.5	0.0
312.5	34.5	375.5	36.0	437.5	0.0	501.5	8.5	564.5	0.0
313.5	33.1	376.5	36.0	438.5	0.0	502.5	5.6	565.5	0.0
314.5	32.0	377.5	36.1	439.5	0.0	503.5	2.5	566.5	0.0
315.5	31.1	378.5	36.2	440.5	0.0	504.5	0.5	567.5	0.0
316.5	30.6	379.5	36.4	441.5	0.0	505.5	0.0	568.5	1.0
317.5	30.2	380.5	36.4	442.5	0.0	506.5	0.0	569.5	4.9
318.5	29.5	381.5	36.2	443.5	0.0	507.5	0.0	570.5	8.3
319.5	28.2	382.5	35.6	444.5	0.0	508.5	0.0	571.5	11.4
320.5	26.7	383.5	34.8	445.5	0.0	509.5	0.0	572.5	13.0
321.5	23.1	384.5	33.8	446.5	0.0	510.5	0.0	573.5	15.3
322.5	20.8	385.5	32.4	447.5	1.6	511.5	2.4	574.5	15.5
323.5	19.6	386.5	30.2	448.5	4.9	512.5	4.5	575.5	17.0
324.5	18.4	387.5	27.4	449.5	8.3	513.5	6.0	576.5	17.0
325.5	17.7	388.5	24.4	450.5	11.6	514.5	7.5	577.5	17.2
326.5	16.2	389.5	21.6	451.5	14.9	515.5	9.1	578.5	17.6
327.5	14.0	390.5	18.9	452.5	18.1	516.5	10.0	579.5	17.7
328.5	11.7	391.5	16.0	453.5	21.4	517.5	11.2	580.5	17.8
329.5	9.4	392.5	13.3	454.5	24.7	518.5	12.9	581.5	17.2
330.5	6.4	393.5	10.3	455.5	27.1	519.5	15.0	582.5	17.0
331.5	3.1	394.5	7.1	456.5	28.4	520.5	16.9	583.5	16.7
332.5	0.7	395.5	3.8	457.5	30.3	521.5	18.4	584.5	16.8
333.5	0.0	396.5	1.1	458.5	32.2	522.5	19.6	585.5	17.1
334.5	0.0	397.5	0.0	459.5	33.3	523.5	20.0	586.5	17.1
335.5	0.0	398.5	0.0	460.5	34.2	524.5	21.5	587.5	16.8
336.5	0.0	399.5	0.0	461.5	34.9	525.5	22.5	588.5	16.0
337.5	0.0	400.5	0.0	462.5	35.4	526.5	23.4	589.5	16.5
338.5	0.0	401.5	0.0	463.5	35.9	527.5	24.2	590.5	16.6
339.5	0.0	402.5	1.3	464.5	36.1	528.5	24.7	591.5	16.0
340.5	0.0	403.5	4.3	465.5	36.1	529.5	24.9	592.5	17.3
341.5	0.0	404.5	7.6	466.5	36.2	530.5	25.0	593.5	18.1
342.5	0.0	405.5	10.9	467.5	36.1	531.5	25.0	594.5	18.9
343.5	0.0	406.5	14.2	468.5	35.9	532.5	25.0	595.5	19.7
344.5	0.3	407.5	17.4	469.5	35.9	533.5	25.0	596.5	20.6
345.5	0.0	408.5	20.7	470.5	36.0	534.5	25.0	597.5	21.1
346.5	0.5	409.5	23.7	471.5	35.8	535.5	25.3	598.5	21.2
347.5	2.6	410.5	25.3	472.5	35.6	536.5	25.7	599.5	21.4
348.5	5.9	411.5	26.8	473.5	35.5	537.5	25.9	600.5	21.8
349.5	9.3	412.5	28.2	474.5	35.3	538.5	25.8	601.5	22.2
350.5	12.8	413.5	29.5	475.5	35.2	539.5	25.4	602.5	22.4
351.5	15.8	414.5	30.1	476.5	35.2	540.5	25.1	603.5	22.5
352.5	18.0	415.5	30.8	477.5	35.2	541.5	25.3	604.5	22.5
353.5	21.2	416.5	29.0	478.5	35.2	542.5	25.0	605.5	22.6
354.5	23.1	417.5	29.5	479.5	35.2	543.5	24.7	606.5	23.2
355.5	24.5	418.5	29.1	480.5	35.1	544.5	23.7	607.5	24.4
356.5	25.9	419.5	28.4	481.5	35.1	545.5	21.5	608.5	25.0
357.5	27.4	420.5	26.5	482.5	35.2	546.5	18.2	609.5	26.2
358.5	29.1	421.5	23.4	483.5	35.4	547.5	14.9	610.5	26.7
359.5	30.4	422.5	20.1	484.5	35.4	548.5	11.6	611.5	25.8
360.5	31.2	423.5	18.7	485.5	35.1	549.5	8.2	612.5	24.4
361.5	31.9	424.5	13.5	486.5	35.0	550.5	5.0	613.5	21.2
362.5	32.6	425.5	10.2	487.5	35.0	551.5	1.6	614.5	17.9
363.5	33.2	426.5	6.9	488.5	34.9	552.5	0.0	615.5	14.6
364.5	34.1	427.5	3.6	489.5	34.7	553.5	0.0	616.5	11.2
365.5	34.6	428.5	0.9	490.5	34.6	554.5	0.0	617.5	7.9
366.5	34.7	429.5	0.0	491.5	34.0	555.5	0.0	618.5	4.6
367.5	34.9	430.5	0.0	492.5	32.7	556.5	0.0	619.5	1.5
368.5	34.0	431.5	0.0	493.5	31.1	557.5	0.0	620.5	0.0
				494.5	29.1				

TABLE 6-3. L4A CYCLE (CONTINUED)

Time (sec)	mph	Time (sec)	mph	Time (sec)	mph	Time (sec)	mph	Time (sec)	mph
621.5	0.0	684.5	0.0	747.5	28.4	810.5	34.1	873.5	26.8
622.5	0.0	685.5	0.0	748.5	28.2	811.5	34.0	874.5	27.2
623.5	0.0	686.5	0.0	749.5	28.1	812.5	34.0	875.5	27.7
624.5	0.0	687.5	0.0	750.5	27.7	813.5	33.8	876.5	28.1
625.5	0.0	688.5	0.0	751.5	27.1	814.5	33.4	877.5	28.7
626.5	0.0	689.5	0.0	752.5	26.2	815.5	33.1	878.5	29.1
627.5	0.0	690.5	0.0	753.5	24.5	816.5	32.7	879.5	29.2
628.5	0.0	691.5	0.0	754.5	22.5	817.5	32.2	880.5	29.1
629.5	0.0	692.5	0.0	755.5	20.2	818.5	32.0	881.5	29.0
630.5	0.0	693.5	0.7	756.5	17.7	819.5	31.7	882.5	28.7
631.5	0.0	694.5	2.4	757.5	15.7	820.5	31.5	883.5	28.3
632.5	[illegible]	695.5	3.9	758.5	13.7	821.5	31.1	884.5	28.1
633.5	0.0	696.5	5.4	759.5	11.0	822.5	30.3	885.5	28.0
634.5	0.0	697.5	7.9	760.5	7.8	823.5	30.0	886.5	27.8
635.5	0.0	698.5	10.3	761.5	4.6	824.5	29.9	887.5	27.6
636.5	0.0	699.5	12.4	762.5	2.2	825.5	29.9	888.5	28.9
637.5	0.0	700.5	14.0	763.5	1.5	826.5	29.9	889.5	28.8
638.5	0.0	701.5	15.5	764.5	1.0	827.5	29.8	890.5	27.2
639.5	0.0	702.5	16.6	765.5	0.2	828.5	29.6	891.5	27.7
640.5	0.0	703.5	16.6	766.5	1.5	829.5	29.5	892.5	27.9
641.5	0.0	704.5	16.5	767.5	4.6	830.5	29.4	893.5	27.9
642.5	0.0	705.5	17.4	768.5	7.9	831.5	29.1	894.5	27.9
643.5	0.0	706.5	18.7	769.5	11.2	832.5	28.6	895.5	28.0
644.5	0.0	707.5	19.7	770.5	14.4	833.5	28.0	896.5	28.0
645.5	1.0	708.5	20.5	771.5	16.7	834.5	27.4	897.5	27.9
646.5	3.7	709.5	22.0	772.5	18.0	835.5	26.2	898.5	27.6
647.5	6.1	710.5	22.5	773.5	19.0	836.5	24.6	899.5	27.1
648.5	9.1	711.5	22.3	774.5	20.1	837.5	22.9	900.5	26.7
649.5	11.3	712.5	22.4	775.5	21.4	838.5	21.2	901.5	26.6
650.5	13.3	713.5	23.0	776.5	22.6	839.5	19.9	902.5	26.5
651.5	14.7	714.5	23.4	777.5	24.1	840.5	19.2	903.5	26.5
652.5	15.4	715.5	23.0	778.5	25.7	841.5	19.7	904.5	26.4
653.5	18.0	716.5	22.0	779.5	27.0	842.5	20.5	905.5	26.3
654.5	20.3	717.5	21.1	780.5	27.7	843.5	21.2	906.5	26.2
655.5	21.6	718.5	19.2	781.5	28.0	844.5	21.7	907.5	26.1
656.5	22.9	719.5	16.5	782.5	28.6	845.5	22.3	908.5	25.8
657.5	23.9	720.5	13.5	783.5	28.9	846.5	22.9	909.5	25.8
658.5	24.9	721.5	10.5	784.5	28.9	847.5	23.6	910.5	25.8
659.5	25.5	722.5	7.6	785.5	28.9	848.5	24.5	911.5	25.9
660.5	25.6	723.5	5.4	786.5	28.7	849.5	25.5	912.5	25.6
661.5	26.1	724.5	3.7	787.5	28.4	850.5	26.3	913.5	25.1
662.5	26.2	725.5	2.6	788.5	28.3	851.5	26.6	914.5	24.1
663.5	26.2	726.5	1.3	789.5	28.0	852.5	26.7	915.5	22.9
664.5	26.3	727.5	0.5	790.5	28.2	853.5	26.9	916.5	21.9
665.5	26.4	728.5	1.9	791.5	27.9	854.5	27.1	917.5	21.8
666.5	26.5	729.5	4.9	792.5	27.5	855.5	27.5	918.5	21.7
667.5	26.2	730.5	8.1	793.5	27.5	856.5	28.0	919.5	22.2
668.5	25.7	731.5	11.1	794.5	27.5	857.5	28.4	920.5	23.0
669.5	24.0	732.5	13.3	795.5	27.5	858.5	28.9	921.5	23.7
670.5	22.5	733.5	15.6	796.5	27.5	859.5	28.9	922.5	24.1
671.5	20.0	734.5	17.0	797.5	27.5	860.5	29.1	923.5	24.3
672.5	17.4	735.5	18.8	798.5	27.6	861.5	29.1	924.5	24.7
673.5	15.5	736.5	20.6	799.5	27.8	862.5	28.6	925.5	25.0
674.5	13.0	737.5	22.3	800.5	28.2	863.5	27.8	926.5	25.2
675.5	11.1	738.5	23.8	801.5	29.2	864.5	27.2	927.5	25.2
676.5	7.3	739.5	25.0	802.5	30.5	865.5	26.6	928.5	25.4
677.5	4.6	740.5	26.0	803.5	31.5	866.5	25.4	929.5	25.4
678.5	2.7	741.5	26.8	804.5	32.5	867.5	24.7	930.5	25.1
679.5	1.0	742.5	27.4	805.5	33.0	868.5	24.7	931.5	25.0
680.5	0.0	743.5	27.8	806.5	33.3	869.5	25.0	932.5	25.0
681.5	0.0	744.5	28.1	807.5	33.8	870.5	25.3	933.5	24.9
682.5	0.0	745.5	28.4	808.5	34.2	871.5	25.6	934.5	24.8
683.5	0.0	746.5	28.6	809.5	34.3	872.5	26.0	935.5	24.4

TABLE 6-3. L4A CYCLE (CONTINUED)

Time (sec)	mph	Time (sec)	mph	Time (sec)	mph	Time (sec)	mph	Time (sec)	mph
936.5	24.3	999.5	23.1	1062.5	23.5	1125.5	25.2	1188.5	[illegible]
937.5	24.4	1000.5	23.7	1063.5	24.4	1126.5	25.6	1189.5	[illegible]
938.5	24.7	1001.5	24.3	1064.5	25.2	1127.5	25.9	1190.5	[illegible]
939.5	25.0	1002.5	24.7	1065.5	26.1	1128.5	26.2	1191.5	[illegible]
940.5	24.8	1003.5	25.0	1066.5	26.7	1129.5	26.5	1192.5	[illegible]
941.5	24.9	1004.5	25.3	1067.5	27.1	1130.5	26.7	1193.5	[illegible]
942.5	24.4	1005.5	25.6	1068.5	27.7	1131.5	26.9	1194.5	[illegible]
943.5	24.3	1006.5	25.8	1069.5	28.1	1132.5	27.0	1195.5	[illegible]
944.5	24.8	1007.5	25.2	1070.5	28.1	1133.5	27.9	1196.5	[illegible]
945.5	25.4	1008.5	24.8	1071.5	27.7	1134.5	26.9	1197.5	[illegible]
946.5	25.6	1009.5	23.9	1072.5	27.2	1135.5	26.9	1198.5	2.5
947.5	24.6	1010.5	23.5	1073.5	27.0	1136.5	26.8	1199.5	5.4
948.5	23.0	1011.5	23.1	1074.5	26.8	1137.5	26.6	1200.5	8.1
949.5	21.1	1012.5	22.7	1075.5	25.4	1138.5	26.5	1201.5	10.9
950.5	18.5	1013.5	22.2	1076.5	23.5	1139.5	26.2	1202.5	12.4
951.5	15.2	1014.5	21.8	1077.5	22.0	1140.5	25.7	1203.5	12.9
952.5	12.4	1015.5	21.1	1078.5	21.1	1141.5	25.1	1204.5	12.8
953.5	8.7	1016.5	19.4	1079.5	19.3	1142.5	24.1	1205.5	12.7
954.5	5.4	1017.5	15.9	1080.5	16.5	1143.5	22.5	1206.5	12.9
955.5	2.1	1018.5	12.6	1081.5	13.6	1144.5	20.7	1207.5	13.1
956.5	0.2	1019.5	9.3	1082.5	11.7	1145.5	18.7	1208.5	13.5
957.5	[illegible]	1020.5	[illegible]	1083.5	10.8	1146.5	16.7	1209.5	14.8
958.5	[illegible]	1021.5	[illegible]	1084.5	10.3	1147.5	15.0	1210.5	16.2
959.5	1.0	1022.5	[illegible]	1085.5	8.7	1148.5	12.4	1211.5	17.8
960.5	3.6	1023.5	[illegible]	1086.5	9.3	1149.5	9.1	1212.5	19.2
961.5	8.9	1024.5	[illegible]	1087.5	8.9	1150.5	5.8	1213.5	20.4
962.5	14.3	1025.5	[illegible]	1088.5	8.8	1151.5	2.1	1214.5	21.2
963.5	13.5	1026.5	[illegible]	1089.5	8.7	1152.5	0.4	1215.5	21.7
964.5	16.4	1027.5	[illegible]	1090.5	8.9	1153.5	[illegible]	1216.5	21.8
965.5	19.1	1028.5	[illegible]	1091.5	8.4	1154.5	[illegible]	1217.5	21.6
966.5	19.3	1029.5	[illegible]	1092.5	8.6	1155.5	[illegible]	1218.5	21.4
967.5	20.6	1030.5	[illegible]	1093.5	8.3	1156.5	[illegible]	1219.5	21.4
968.5	21.6	1031.5	[illegible]	1094.5	7.5	1157.5	[illegible]	1220.5	21.7
969.5	22.5	1032.5	[illegible]	1095.5	6.4	1158.5	[illegible]	1221.5	21.9
970.5	23.7	1033.5	[illegible]	1096.5	4.6	1159.5	[illegible]	1222.5	22.0
971.5	25.4	1034.5	[illegible]	1097.5	3.4	1160.5	[illegible]	1223.5	21.8
972.5	26.9	1035.5	[illegible]	1098.5	1.6	1161.5	[illegible]	1224.5	21.6
973.5	27.6	1036.5	[illegible]	1099.5	0.5	1162.5	[illegible]	1225.5	21.5
974.5	28.2	1037.5	[illegible]	1100.5	0.1	1163.5	[illegible]	1226.5	21.4
975.5	28.4	1038.5	[illegible]	1101.5	0.4	1164.5	[illegible]	1227.5	20.0
976.5	28.5	1039.5	[illegible]	1102.5	1.1	1165.5	[illegible]	1228.5	19.8
977.5	28.5	1040.5	[illegible]	1103.5	2.6	1166.5	[illegible]	1229.5	19.4
978.5	29.1	1041.5	[illegible]	1104.5	5.3	1167.5	[illegible]	1230.5	19.4
979.5	27.8	1042.5	[illegible]	1105.5	8.4	1168.5	1.1	1231.5	19.7
980.5	27.4	1043.5	[illegible]	1106.5	11.4	1169.5	3.8	1232.5	19.9
981.5	27.0	1044.5	[illegible]	1107.5	13.4	1170.5	7.1	1233.5	19.7
982.5	26.8	1045.5	[illegible]	1108.5	14.3	1171.5	10.4	1234.5	19.5
983.5	26.2	1046.5	[illegible]	1109.5	15.2	1172.5	13.6	1235.5	16.5
984.5	25.9	1047.5	[illegible]	1110.5	17.1	1173.5	17.0	1236.5	14.3
985.5	25.5	1048.5	[illegible]	1111.5	19.1	1174.5	19.9	1237.5	11.5
986.5	24.6	1049.5	[illegible]	1112.5	20.5	1175.5	22.1	1238.5	[illegible]
987.5	23.4	1050.5	[illegible]	1113.5	21.1	1176.5	23.2	1239.5	7.0
988.5	21.7	1051.5	[illegible]	1114.5	21.2	1177.5	23.7	1240.5	5.8
989.5	21.5	1052.5	[illegible]	1115.5	21.4	1178.5	22.7	1241.5	3.2
990.5	21.7	1053.5	2.6	1116.5	21.6	1179.5	21.2	1242.5	1.6
991.5	22.2	1054.5	5.8	1117.5	22.1	1180.5	18.4	1243.5	[illegible]
992.5	22.7	1055.5	9.4	1118.5	22.7	1181.5	15.1	1244.5	[illegible]
993.5	22.9	1056.5	12.2	1119.5	23.4	1182.5	11.4	1245.5	[illegible]
994.5	22.5	1057.5	15.5	1120.5	24.2	1183.5	8.5	1246.5	[illegible]
995.5	22.9	1058.5	17.7	1121.5	24.7	1184.5	5.1	1247.5	[illegible]
996.5	22.9	1059.5	19.2	1122.5	25.0	1185.5	1.9	1248.5	[illegible]
997.5	22.7	1060.5	20.9	1123.5	24.9	1186.5	0.1	1249.5	[illegible]
998.5	22.7	1061.5	22.4	1124.5	24.6	1187.5	[illegible]	1250.5	[illegible]

TABLE 6-3. L4A CYCLE (CONTINUED)

Time (sec)	mph	Time (sec)	mph
1251.5	[illegible]	1314.5	[illegible]
1252.5	1.[illegible]	1315.5	[illegible]
1253.5	1.[illegible]	1316.5	[illegible]
1254.5	1.[illegible]	1317.5	[illegible]
1255.5	1.[illegible]	1318.5	[illegible]
1256.5	1.3	1319.5	[illegible]
1257.5	2.3	1320.5	[illegible]
1258.5	3.5	1321.5	[illegible]
1259.5	4.[illegible]	1322.5	[illegible]
1260.5	5.8	1323.5	[illegible]
1261.5	7.1	1324.5	[illegible]
1262.5	9.[illegible]	1325.5	[illegible]
1263.5	10.2	1326.5	[illegible]
1264.5	[illegible]	1327.5	[illegible]
1265.5	9.[illegible]	1328.5	[illegible]
1266.5	8.1	1329.5	[illegible]
1267.5	8.2	1330.5	[illegible]
1268.5	9.9	1331.5	[illegible]
1269.5	12.5	1332.5	[illegible]
1270.5	15.5	1333.5	[illegible]
1271.5	18.2	1334.5	[illegible]
1272.5	20.2	1335.5	[illegible]
1273.5	21.4	1336.5	[illegible]
1274.5	22.[illegible]	1337.5	[illegible]
1275.5	22.8	1338.5	3.1
1276.5	23.3	1339.5	6.4
1277.5	23.[illegible]	1340.5	[illegible]
1278.5	24.3	1341.5	12.5
1279.5	24.5	1342.5	14.1
1280.5	24.2	1343.5	15.[illegible]
1281.5	23.7	1344.5	17.8
1282.5	23.5	1345.5	18.9
1283.5	23.5	1346.5	19.[illegible]
1284.5	[illegible]	1347.5	20.[illegible]
1285.5	23.5	1348.5	21.8
1286.5	23.5	1349.5	22.[illegible]
1287.5	23.7	1350.5	22.3
1288.5	24.1	1351.5	22.2
1289.5	24.3	1352.5	21.[illegible]
1290.5	24.6	1353.5	21.4
1291.5	24.[illegible]	1354.5	[illegible]
1292.5	25.2	1355.5	20.2
1293.5	25.5	1356.5	19.8
1294.5	25.7	1357.5	19.1
1295.5	25.[illegible]	1358.5	18.[illegible]
1296.5	26.1	1359.5	17.9
1297.5	26.8	1360.5	18.[illegible]
1298.5	27.4	1361.5	14.7
1299.5	28.1	1362.5	12.5
1300.5	28.7	1363.5	9.5
1301.5	29.1	1364.5	[illegible]
1302.5	29.1	1365.5	3.[illegible]
1303.5	29.5	1366.5	1.7
1304.5	28.4	1367.5	[illegible]
1305.5	[illegible]	1368.5	[illegible]
1306.5	[illegible]	1369.5	[illegible]
1307.5	[illegible]	1370.5	[illegible]
1308.5	13.2	1371.5	[illegible]
1309.5	[illegible]	1372.5	[illegible]
1310.5	6.8		
1311.5	3.3		
1312.5	[illegible]		
1313.5	[illegible]		

TABLE 6-4. APPROXIMATED LA4 CYCLE

Segment Mode	V_s(mph)	V_f(mph)	t(sec)	a_i(g's)x10^{-2}
1I	0	0	19.5	0
2a	0	21.5	10	9.85
3c	21.5	-	7	0
4d	21.5	15	3	9.93
5a	15	21	3	9.16
6d	21	16	4	5.73
7a	16	24	5	7.33
8c	24	-	17	0
9a	24	31	5	6.42
10c	31	-	30	0
11d	31	0	9	16.78
12I	0	-	37	0
13a	0	26	8	14.90
14c	26	-	12	0
15d	26	16	4	11.46
16a	16	47	17	8.36
17c	47	-	12	0
18a	47	55.5	10	3.90
19c	55.5	-	28	0
20c	52.5	-	22	0
21a	52.5	55.5	2	6.88
22c	55.0	-	8	0
23d	55	49.5	5	5.50
24c	49.5	-	11	0
25d	49.5	0	31	7.32

I = idle d = deceleration

a = acceleration c = cruise

TABLE 6-4. APPROXIMATED LA4 CYCLE (CONTINUED)

Segment Mode	V_s(mph)	V_f(mph)	t(sec)	a_i(g's)$\times 10^{-2}$
26I	0	0	13	0
27a	0	34.5	19	8.32
28c	34.5	-	19	0
29d	34.5	0	13	12.16
30I	0	-	5	0
31a	0	29.2	11	12.17
32c	29.2	-	7	0
33d	29.2	0	9	14.87
34I	0	-	18	0
35a	0	35.5	14	11.62
36c	35.5		30	0
37d	35.5	0	14	11.62
38I	0		5	0
39a	0	25	17	7.28
40c	25	-		0
41d	25	0	8	14.32
42I	0		16	0
43a	0	17.5	6	13.37
44c	17.5	-	20	0
45a	17.5	26.5	17	2.43
46d	26.5	0	9	13.50
47I	0		25	0
48a	0	26	16	7.45
49c	26	-	7	0
50d	26	0	12	9.93

I = idle d = deceleration

a = acceleration c = cruise

TABLE 6-4. APPROXIMATED LA4 CYCLE (CONTINUED)

Segment Mode	V_s(mph)	V_f(mph)	t(sec)	a_i(g's)x10^{-2}
51I	0	-	13	0
52a	0	22.5	16	6.45
53c	22.5	-	8	0
54d	22.5	0	10	12.89
55a	0	27.9	14	9.13
56c	27.9	-	9	0
57d	27.9	0	15	8.53
58a	0	28.2	14	9.23
59c	28.2	-	20	0
60a	28.2	33.6	5	4.95
61d	33.6	30	6	2.75
62c	30	-	10	0
63d	30	19	9	5.60
64a	19	28	13	3.17
65c	28	-	13	0
66d	28	25	4	3.44
67a	25	28	8	1.72
68c	28	-	32	0
69d	28	21.5	10	2.98
70a	21.5	25	6	2.67
71c	25	-	24	0
72d	25	0	9	12.73
73I	0	-	2	0
74a	0	27.5	13	9.70
75d	27.5	-	11	11.46

I = idle d = deceleration

a = acceleration c = cruise

TABLE 6-4. APPROXIMATED LA4 CYCLE (CONTINUED)

Segment Mode	V_s(mph)	V_f(mph)	t(sec)	a_i(g's)x10^{-2}
76d	27.5	21.5	6	4.58
77a	21.5	24	4	2.86
78c	24	-	19	0
79d	24	0	11	10.00
80I	0		28	0
81a	0	27	10	12.38
82d	27	8.5	13	6.52
83c	8.5	-	6	0
84d	8.5	0	7	5.57
85a	0	26	20	5.96
86c	26	-	21	0
87d	26	0	11	10.83
88I	0	-	15	0
89a	0	23	9	11.71
90d	23	0	10	10.54
91I	0	-	9	0
92a	0	21	17	5.66
93c	21	-	15	0
94d	21	0	16	6.02
95I	0	-	7	0
96a	0	9	11	3.75
97c	9	-	5	0
98a	9	24	9	7.64
99c	24	-	12	0
100a	24	28	10	1.83

I = idle　　d = deceleration

a = acceleration　　c = cruise

TABLE 6-4. APPROXIMATED LA4 CYCLE (CONTINUED)

Segment Mode	V_s(mph)	V_f(mph)	t (sec)	a_i(g's)x10^{-2}
101c	28	-	6	0
102d	28	0	9	14.26
103I	0	-	24	0
104a	0	21	9	10.69
105c	21	-	11	0
106d	21	0	10	9.63
107I	0	-	6	0

Note: On Equations 5-1 through 5-5,

if mode = a (Eqn 5-3)

$$V_f = V_{ui}$$

$$V_s = V_{Li}$$

mode = d (Eqn 5-4)

$$V_s = V_{ui}$$

$$V_f = V_{Li}$$

TABLE 6-5. SUMMARY

PARAMETER	USED IN	INTERPRETATION	ORIGIN	VALUE
p^2_{idle}	X_1	SPL of idling vehicle	Measured	Table 6-2
T_{idle}	X_1	Total idle time during cycle (sec)	Vehicle utilization model	Table 6-1
K_{ij}, K_{2j}	X_2	Slope and intercept of coast-by and engine SPL (dBA)	Equations 6-4-1 and 6-4-2	Section 6-4-2
Vck	X_2	Cruise velocity, cruise subcycle K (mph)	Definition	Table 6-4
Kcgk	X_2	Cruise drive ratio subcycle K [mph/(rpm/1000)]	Defined by vehicle configuration	Table 6-6
Tcrk	X_2	Time of cruise subcycle K (sec)	Vehicle utilization model	Table 6-4
Nc	X_2	Number of cruise subcycles	Vehicle utilization model	Table 6-1
a_1, a_2	X_3	Slope and intercept of acceleration SPL (dBA)	Equation 6-4-3	Section 6-4-3
A_{ai}	X_3	Acceleration during acceleration subcycle i	Definition	Table 6-4
Kagj	X_3	Acceleration drive ratio gear j	Definition	Table 6-6
Sj	X_3	Step function	Equation 6-5-1	Section 6-5
V_{ui}	X_3	Upper velocity of acceleration subcycle i	Definition	Table 6-4
V_{Li}	X_3	Lower velocity of acceleration subcycle i	Definition	Table 6-4

TABLE 6-5. (CONTINUED)

PARAMETER	USED IN	INTERPRETATION	ORIGIN	VALUE
Na	X_3	Number of acceleration subcycles	Definition	Table 6-1
Ng	X_3	Number of gear ratios	Definition	Table 6-6
Nd	X_4	Number of deceleration subcycles	Definition	Table 6-1
adi	X_4	Deceleration during deceleration subcycle i	Definition	Table 6-4
K_{1j}, K_{2j}	X_4	Coast-by and engine SPL slope and intercept	Equation 6-4-2	Section 6-4-2
V_{ui}	X_4	Upper velocity of deceleration subcycle i	Definition	Table 6-4
V_{Li}	X_4	Lower velocity of deceleration subcycle i	Definition	Table 6-4

TABLE 6-6. FINAL DRIVE RATIOS FOR THE SAAB 99 AND PEUGEOT 504 GLD VEHICLES

Vehicle	Gear	Kg (mph/1000 RPM)
Saab	4	18.9
	3	13.8
	2	9.23
	1	5.66
Peugeot	4	18.0
	3	12.5
	2	8.3
	1	4.9

APPENDIX

REPORT OF NEW TECHNOLOGY

The work performed under this contract, while leading to no new inventions, has provided detailed characteristics on acoustics, exhaust emissions, odor, and fuel economy characterizations of small, high-speed internal combustion engines. This report focuses upon the acoustic aspects of small, high-speed internal ombustion engines.

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