TRANSPORT and ROAD
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TRRL REPORT LR 494

AN ASSESSMENT OF THE FERGUSON FOUR-WHEEL DRIVE AND ANTI-LOCK BRAKING SYSTEM

PART I – SOME QUANTITATIVE TESTS

by

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Part II of this Report, an assessment in police operation, has been published by the Home Office.

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Safety Department
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CONTENTS

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PART I – SOME QUANTITATIVE TESTS

Twenty-one Ford Zephyr saloon cars were converted to the Ferguson 4-wheel drive and anti-lock braking system at the instigation of the Ministry of Technology to obtain user experience with the system. Preliminary instrumented investigations indicated that some alterations and adjustments were necessary to optimise the braking system and make it acceptable for use. The optimized system enabled shorter braking distances to be obtained with the anti-lock braking system in operation than without it on both wet and dry surfaces. Use of the anti-lock braking system also resulted in the car remaining directionally stable under all conditions of braking.

Some tests indicated that the four-wheel drive system had little effect on acceleration or maximum speed of the car under dry road conditions.

1. INTRODUCTION

It is known that maximum braking force is obtained at some point before a braked-wheel locks and that the braking force achieved depends on the frictional characteristics of the particular tyre and road surface. In practice, an emergency stop with a full application of the brakes causing all wheels to lock will achieve a shorter braking distance than if the driver searches for the pedal load which would result in peak braking being obtained. Locked wheels however may result in vehicle instability and loss of directional control. Earlier investigations by the Laboratory[1] indicated that use of sensing devices to control wheel locking automatically could result in directional stability being maintained with some retention of steering control, and better use of the available peak braking force could reduce the minimum braking distances obtainable on some surfaces. The first commercial application of an anti-wheel locking system available to the public was one designed by Harry Ferguson Research Ltd., using the Dunlop Maxaret unit fitted in conjunction with the Ferguson four-wheel drive system to the Jensen FF car.

To determine the practical advantage of this system on mass produced cars in road use, the Ministry of Technology (now Department of Trade and Industry) arranged for Harry Ferguson Research to convert a batch of Ford Zephyr saloon cars. The majority of these were placed in service with various police forces for user trials in comparison with similar unmodified cars. One of the batch of modified cars was obtained by the Laboratory and this part of the Report describes the results of some quantative tests mainly to determine the braking performance obtained with this anti-lock braking system, but including some tests to assess the effect of the four-wheel drive system on performance. Part II of the Report concerning the assessment of the converted car in police service has been prepared by the Police Scientific Development Branch of the Home Office[2].

2. DESCRIPTION OF CAR

Basically a 1968/69 Ford Zephyr 6 saloon, the car had been modified for police use by the Ford Motor Co. Ltd., and then converted to the Ferguson four-wheel drive and anti-lock braking system by Harry Ferguson Research Ltd. Specifications for the car before and after this conversion are shown in Table 1. The major modifications to the standard production car were a 2994 c.c. engine in place of the normal 2495 c.c. engine, Dunlop S.P.68 tyres and provision for additional electrical equipment. Installation of the four-wheel drive and anti-lock braking systems also necessitated replacement of the Macpherson strut front suspension by a wishbone and coil spring suspension, raising and moving the front located engine slightly to the nearside, fitting slightly larger front brake discs, brake pads of a different material and a different brake servo unit.

The only difference affecting the braking system of the car under test from others converted in the same batch was the fitting of a make-and-break switch in the electrical circuit of the Maxaret solenoid which enabled the anti-lock braking system to be switched off and the brake system used as a normal system.

Prior to the tests and after an initial settling down period the car was checked by Harry Ferguson Research Ltd.

2.1 Four-wheel drive systems

The Ferguson system has been fully described in the technical press[3]. All wheels are driven through a centre differential and control units which permit the driving torque to be divided between the front and rear wheels, in this car 37 per cent to the front wheels and 63 per cent to the rear wheels, and also permits a speed difference between them, the rear propeller shaft being able to over-run the front propeller shaft by 5¼ per cent and the front wheels to over-run the rear wheels by 20 per cent. Both wheels on one axle can neither spin nor lock up without both of the wheels on the other axle locking or spinning up. However one wheel on each axle can spin or lock as a pair without the other wheels.

2.2 Anti-lock braking system

As the front and rear wheel drives are interconnected in their transmission system, Harry Ferguson Research Ltd. utilise a single Dunlop Maxaret sensing unit driven from the centre differential to control the locking of all four wheels. When the angular deceleration of the road wheels during braking (and therefore the transmission system) exceeds a value predetermined by a spring setting in the control unit, an electronic solenoid valve is made which operates a valve in the vacuum servo system and reverses the action of the vacuum servo unit. By exhausting the side of the servo diaphragm otherwise under atmospheric pressure and reducing the vacuum on the opposite side, the servo effort to the master cylinder is reduced and less braking effort is applied to the wheels. At the same time this applies a reaction at the brake pedal which can be detected by the driver. During a braking stop in which the anti-lock device is caused to operate, this is felt by the driver as a pulsing of the brake pedal. In theory this indication that the anti-lock device is operating informs the driver that maximum braking effort consistent with tyre road adhesion is being applied. With a vacuum of 50 cm/hg a pushing off force of about 100 kg is exerted at the brake pedal. It should be noted that the anti-lock braking system will not totally prevent the driver locking the wheels: if the load applied to the brake pedal by the driver is sufficiently in excess of the pushing off force the wheels will lock. The Maxaret unit was initially set to operate at a wheel deceleration of 1.1 g. The over-run setting, which is governed by the inertia of the fly-wheel and controls the maximum time for which the brakes can remain off was originally set at 2.25 g.

3. INSTRUMENTATION

Braking distance and the speed of the car on application of the brakes were measured by a fifth wheel. Other necessary data were recorded continuously on film by a galvanometer recorder as follows:

Deceleration	- from a potentiometric decelerometer fixed to the floor of the passenger compartment.
Front brake line pressure Rear brake line pressure	from transducers between the tandem master cylinder and the respective brakes.
Brake pedal load	- from a load cell attached to the brake pedal pad.
Vacuum level	- from a transducer in the vacuum line between the vacuum tank and non-return valve in the engine manifold line.
Maxaret operation	- from the make-and-break of the electrical circuit of the Maxaret solenoid.
Transmission speed	- from a tachometer generator driven from the rear propeller shaft.
Timing trace	- 1- c/s trace built into the recorder.

Examples of recordings obtained are shown in Plate 1.

The speed of the vehicles in the handling tests was taken from a fifth wheel speedometer. Maximum speed and acceleration were obtained from the police specified speedometers fitted to the cars, the latter in conjunction with a stop watch.

4. DESCRIPTION OF TESTS

Although the tests were carried out mainly with the Laboratory's own car, occasional checks were carried out using other cars from the batch, sometimes with Police drivers, to ensure that the results applied generally.

4.1 Braking tests

Minimum braking distances with the anti-lock braking system in use and with it switched out of operation were obtained on three different surfaces:-

a dry fine textured asphalt surface with a high resistance to skidding;

a wet fine textured asphalt surface with a good resistance to skidding, and

a wet mastic asphalt surface with a poor resistance to skidding.

To obtain minimum braking distances the driver applied the brake pedal as quickly as possible and as hard as possible when the anti-lock braking system was not in operation, or until the push back force on the pedal was felt when the system was in use.

To determine the effect on directional stability further braking tests were made as follows: on a curve of 46 m radius on the wet slippery surface; with two wheels on the same side on a good skid resistant surface, and the other two on the slippery surface; when passing from a slippery surface to a surface with a good resistance to skidding.

4.2 Vehicle handling

In an attempt to assess the effect of four-wheel drive, tests were made with the car in four-wheel drive, with the car driven through the front wheels only (rear propeller shaft removed) and through the rear wheels only (front propeller shaft removed) rather than by comparison with a two-wheel drive car since the effect of differences in front suspension might have masked the effect due to four-wheel drive.

Three drivers carried out two manouevres each to assess the handling characteristics in these conditions. The manouevres are shown in Fig. 1 and both were carried out on a wet surface with low skid resistance and on a dry high skid resistant surface. With the driver attempting to keep the speed constant over the length of each test run, runs were made at increasing speeds until the car failed to make the course by hitting a marker. Having thus failed to complete the course correctly, the test speeds were slowly decreased until a clear run was again obtained. This speed was used to compare the results.

4.3 Maximum speed and acceleration tests

Maximum speed and acceleration times were measured over 2.2 km of the test track on two four-wheel drive cars and two standard two-wheel drive cars for comparison. These tests were carried out by the same driver and were all completed within the same 30 minute period in order to minimise any temperature or other effects.

5. RESULTS

5.1 Braking system performance

With the original Maxaret sensing unit settings of 1.1 g deceleration and 2.25 g over-run it was observed that longer distances were obtained when a driver applied the foot-brake with just sufficient pedal pressure so that pedal push back indicated that the anti-lock braking system was operating than if he applied a load in excess of this but not sufficient to over-ride the push back and lock the wheels. On the surface with a low skid resistance the braking distances obtained with the anti-lock braking system in use were always shorter than those obtained with it switched out or with a similar two-wheel drive car having a normal brake system (Fig. 2). On the surfaces with a good skid resistance however, while the best braking distances obtained with the system in use were longer than the locked wheel stops at speeds up to about 80 km/h and shorter from higher speeds, the distances with a pedal load just sufficient to cause the anti-lock braking system to operate were longer at all speeds (Figs 3 and 4). As Fig. 4 shows the braking distances with the system in use could be up to 40 per cent longer than the locked wheel distances on a dry surface.

Analysis of the records showed that in stops from the same speed on the good skid resistant surface, the anti-lock braking system came into operation at pedal loads which varied from 20 kg to 100 kg with corresponding variations in line pressures and car deceleration despite the tests being carried out on a uniform surface. The Maxaret was also shown to be operating in some instances when the trace of propeller shaft rotational speed indicated a steady deceleration without wheel locking. It was also noted from the records that the 'brake off' period was frequently longer than the 'brake on' period.

In conjunction with Harry Ferguson Research Ltd., a number of adjustments and alterations were tried in order to overcome or at least minimise these effects. The wheel deceleration at which the Maxaret would operate was first raised from 1.1 g to 1.2 g in an attempt to damp out the spurious Maxaret operations, but this resulted in excessive wheel locking on the wet slippery surface. Reduction and complete removal of the all weather valve governing the rate of re-application of the brakes to increase the 'brake on' period had no measurable effect on the braking distance obtained on the better surfaces. Increasing the over-run setting, which entailed using a lighter flywheel in the Maxaret sensing unit, resulted in more consistent operation of the system. Tests indicated that optimum braking performance was obtainable with an over-run setting of 2.5 g. The new settings (deceleration = 1.1 g; over-run = 2.5 g) gave shorter distances than the original settings on all surfaces. On the dry high skid resistant surface, the light brake application technique resulted in braking distances only slightly longer than the locked wheel stop (about 4 per cent longer from 65 km/h), while the heavier applications with the system operating were shorter (about 10 per cent shorter from 65 km/h), (Fig. 5). On the wet slippery surface from 65 km/h, the braking distances with the new settings were about 20 per cent shorter than the locked wheel distances compared with about 10 per cent shorter with the original setting (Fig. 6).

Check tests with one or two of the police cars, both with the original settings and new settings, confirmed these results and all cars were subsequently modified.

5.1.1 Vacuum supply

Supply of vacuum for operating the brake servo and regulating brake pedal push back was obtained from the depression in the inlet manifold with a storage tank of 10 cm^3 capacity. The maximum vacuum obtainable in normal operating conditions on the test car was about 58 cm Hg. Care was taken to see that maximum vacuum was available at the beginning of each test. The record showed that the vacuum fell rapidly throughout each brake stop because with the anti-lock braking system operating, intervals between operation of the system were insufficient for vacuum recovery. As Fig. 7 shows with the one vacuum tank, vacuum could be zero after about 9 operations of the unit and stops from over 65 km/h on the slippery surface resulted in the wheels locking up during the latter part of the stop. Doubling the capacity of the vacuum tanks resulted in a reduced fall off (to 10 cm Hg after about 9 operations) and although recovery was not so great in between operations, this was sufficient to permit the anti-locking system to operate throughout a stop from 80 km/h on the slippery surface. This progressive reduction in vacuum throughout a stop must be considered an undesirable feature because as the vacuum falls, the pushing off pressure on the brake system servo is also reduced and more of the driver's manual effort will be applied to the brake system. On the more slippery surfaces this could lead to locked wheels since in a real emergency there would probably be a tendency to press harder on the brake pedal if a collision became imminent.

During sustained high speed runs at constant throttle opening, as occurs on motorways, it was noted that the vacuum fell to 10 cm Hg although there was no detectable leak in the system and the brakes were not used. At this level the driver would receive little benefit from the system in an emergency stop and it was considered that a low vacuum warning device should be fitted if a vacuum gauge was not installed.

All other cars in the batch have since been fitted with an additional vacuum tank and a low vacuum warning light. No reports have been received of vacuum failure on cars in Police use, however.

5.1.2 Directional stability and steering control

The results of tests to determine the directional stability and steering control of the car under emergency braking are given in Table 2. These show that the anti-lock braking system permitted the car to be kept to the required path both when braking on a curve and when braking with different wheels on surfaces having different skidding resistances. However, without the system in use inter-connection of the wheels by the four-wheel drive avoided directional instability due to locking of the rear wheels only, as, for example, when passing from a low to a high skid resistant surface. It did not prevent instability when both wheels on the same side were on a surface with a lower skid resistant surface than the other two wheels; if the brakes were then applied hard enough to lock all wheels the car rotated about the vertical axis while travelling in a seemingly straight line. At lower brake applications, when only the wheels on the more slippery surface locked, the car deviated in a wide arc.

5.2 Handling

The results of the handling tests (Table 3), both on the dry high skid resistant surface and on the Bridport gravel with a lower skid resistance were not conclusive. Police reports, however, indicate that in conditions of very limited traction cars converted to the four-wheel drive system were able to proceed and manoeuvre in conditions in which other vehicles were unable to move. Details are given in the Police User Assessment (Part II of this Report).

5.3 Maximum speed

There was no practical difference in the maximum speeds obtained with the four-wheel drive and the normal two-wheel drive cars. As expected the four-wheel drive car of the Laboratory and the two-wheel drive car of the Military Vehicles Experimental Establishment gave slightly higher maximum speeds at 155 km/h. The police cars, when tested, carried a lot of extra equipment and had done a much higher mileage.

5.4 Acceleration

Acceleration times to different speeds (Fig. 8) showed little difference between the two-wheel drive cars. The police four-wheel drive car took about 2 seconds longer than the two-wheel drive cars to reach 110 km/h, the TRRL four-wheel drive car about 3 seconds less. Both police cars were similarly equipped and differences are most likely to be due to factors other than four-wheel drive.

In considering these results it should be remembered that the conversion added 109 kilogrammes to the car weight.

6. CONCLUSIONS

1. Although it is considered that ideally each wheel should be individually sensed, the results of these tests show that improved braking performance and directional stability can be obtained using one sensing unit in conjunction with inter-connected front and rear wheel drive to control the locking of all four wheels.

2. The anti-lock braking system permitted shorter braking distances than those obtainable in locked emergency stops on all surfaces.

3. The brake system was still driver dependent. A brake application only just sufficient to cause the anti-lock braking system to operate could result in slightly longer distances (on dry surfaces approximately 4 per cent longer but on wet surfaces less than the locked wheel distances), too heavy a brake application would result in wheel locking.

4. The vacuum supply system was insufficient to maintain full vacuum during successive operations of the anti-lock braking system. This could result in the driver pushing through to locked wheels as the 'brake off' force deteriorated during a stop and on the very slippery surface used in the tests the anti-lock braking system ceased to work during stops from speeds of above about 65 km/h. Vacuum from the engine induction manifold was not sufficient to maintain operation under all braking conditions.

5. The anti-lock braking system, when the vacuum supply was sufficient, enabled the car to be stopped without directional instability under all braking and surface conditions and enabled steering control to be maintained during emergency braking.

6. The four-wheel drive by inter-connecting front and rear wheels stopped the rear wheels only from locking up and prevented the resulting directional instability. When the wheels on one side of the car were on a surface with a different skid resistance to those on the other side however, wheel locking and directional instability could occur when braking without the anti-lock braking system

7. The maximum speed and acceleration on a good dry road surface was not adversely affected by the conversion of the cars to four-wheel drive despite the increased weight.

7. ACKNOWLEDGEMENTS

The work described in this Report was carried out by Messrs R N Kemp, B P Chinn and B Brock of the Vehicle Performance Section of Vehicles Division. The assistance given by Harry Ferguson Research Ltd. in carrying out adjustments to the brake system, by the Police Scientific Development Branch of the Home Office and the Thames Valley Constabulary in providing police cars and drivers and the Military Vehicle Experimental Establishment for the loan of cars is gratefully acknowledged.

8. REFERENCES

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2. MARRIOTT, G N and J RUSSELL, Editors. The Ferguson four-wheel drive system. Part II – An Assessment in Police Operation. *Report* 11/75. London, 1972 (Police Scientific Development Board and Police Research Services Branch, Home Office).

3. BULMER, C. The Ferguson R5 prototype. *Motor*, August 20 1966, 15-18.

TABLE 1

Details of car before and after Ferguson Formula conversion

	Before conversion	After conversion
ENGINE	FORD 2994 cc V6	FORD 2994 cc V6 raised 2 mm and moved 38 mm to left-hand side.
TRANSMISSION	FORD C4 Automatic Rear Axle Ratio 3.70:1 31.25 km/h at 1000 rpm.	FORD C4 Automatic with P134 four-wheel drive. Front and Rear Axle Ratios 3.70:1 overall ratio 3.77:1 (30.67 km/h at 1000 rpm).
SUSPENSION	FRONT:- Independent Macpherson strut. REAR:- Independent semi trailing arms and coil springs.	FRONT:- Independent with twin wish bones and coil springs, new tie bars and anti-roll bar. REAR:- Unchanged.
BRAKES	FRONT:- Girling 24 cm diam. discs, 135 cm^2 lining area 1370 cm^2 swept area. REAR:- 25 cm diam. discs; 155 cm^2 lining area; 897 cm^2 swept area. Vacuum Servo: Girling Supervac Type 50 Pedal Ratio:- 3.8:1 Brake Ratio:- 65% Front, 35% Rear.	FRONT:- Girling 25 cm diam. discs, 135 cm^2 lining area 1452 cm^2 swept area. Ferodo 2430 Pads. REAR:- Unchanged. Vacuum Servo:- Dunlop CT 84 Pedal Ratio:- 3.8:1 Brake Ratio:- 66.5% Front, 33.5% Rear. Max. Normal Vacuum:- 58 cm Hg.
TYRES	1.70 x 14 Dunlop SP68 Front:- 1.45 m Rear:- 1.49 m	Unchanged Front:- 1.49 m Rear:- 1.49 m
WHEELBASE	2.92 m	Unchanged
WEIGHT	Front 780 kg 57% Rear 593 kg 43% TOTAL 1373 kg	Front 875 kg 59% Rear 607 kg 41% TOTAL 1482 kg

TABLE 2

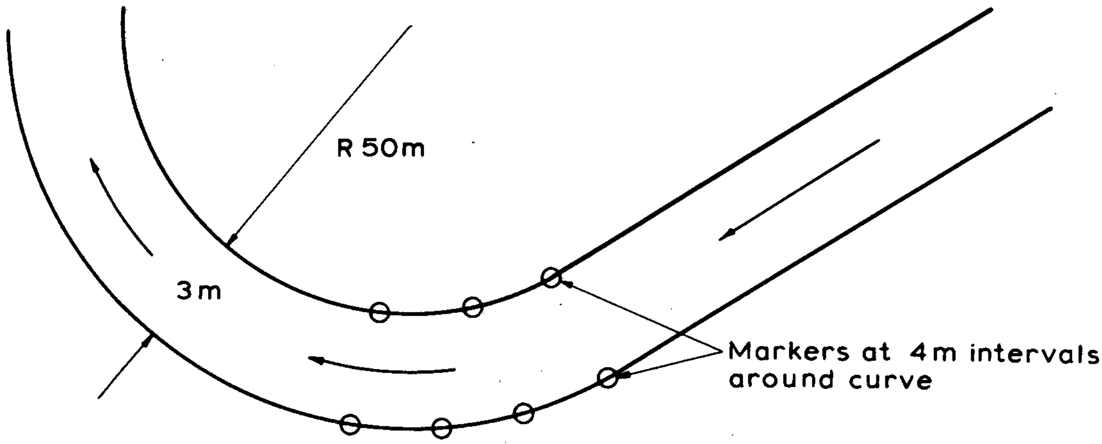
Results of tests to show directional stability and steering control in emergency braking

Test	Initial speed (km/h)	DIRECTIONAL STABILITY			STEERING CONTROL		
		Ferguson 4-wheel drive WITH anti-lock braking system	Ferguson 4-wheel drive WITHOUT anti-lock braking system	Standard 2-wheel drive with normal brake system	4 w.d. with anti-lock braking	4 w.d. without anti-lock braking	2 w.d. normal brake system
Braking on a 50 m radius curve	48	Car remained on curved path until it stopped.	Car slid out of curve with slight tendency for rear end to swing out.	Car slid out of curve with tendency for rear end to swing out.	Adequate	Nil	Nil
Braking with wheels on one side on high skid resistant surface. Other 2 wheels on low skid resistant surface.	56	Car tended to pull towards high skid resistant surface but could be easily controlled.	Car spun through 180°	Car spun through 180°	Adequate to keep car on intended path.	Nil	Nil
Braking when passing from low skid resistant surface, to high skid resistant surface.	56	Car kept straight.	Car kept straight.	Car spun through 180°	Retained.	Nil	Nil
Braking when travelling from high to low skid resistant surface.	64 56	Car kept straight.	Car kept straight.	Car kept straight.	Retained.	Nil	Nil

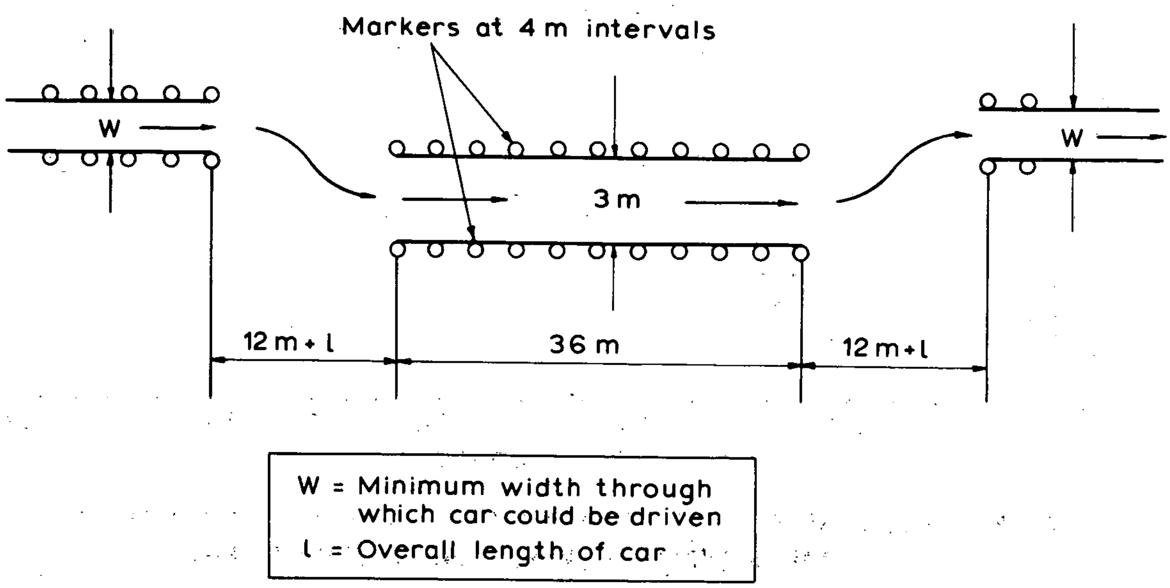
TABLE 3

Maximum speeds at which handling tests were successfully completed

Driver	J M	G B	F L
Car and manoeuvre	km/h	km/h	km/h
DRY CHICANE			
4 wheel drive	69	71	66
Front wheel drive	61	69	64
Rear wheel drive	68	69	71
DRY CURVE			
4 wheel drive	64	61	61
Front wheel drive	63	60	61
Rear wheel drive	60	61	60
WET CHICANE			
4 wheel drive	64	55	60
Front wheel drive	60	58	-
Rear wheel drive	61	56	58
WET CURVE			
4 wheel drive	48	47	53
Front wheel drive	51	47	50
Rear wheel drive	51	48	50



(a) Curved path



(b) Overtaking or chicane path

Fig. 1. HANDLING TEST MANOEUVRES

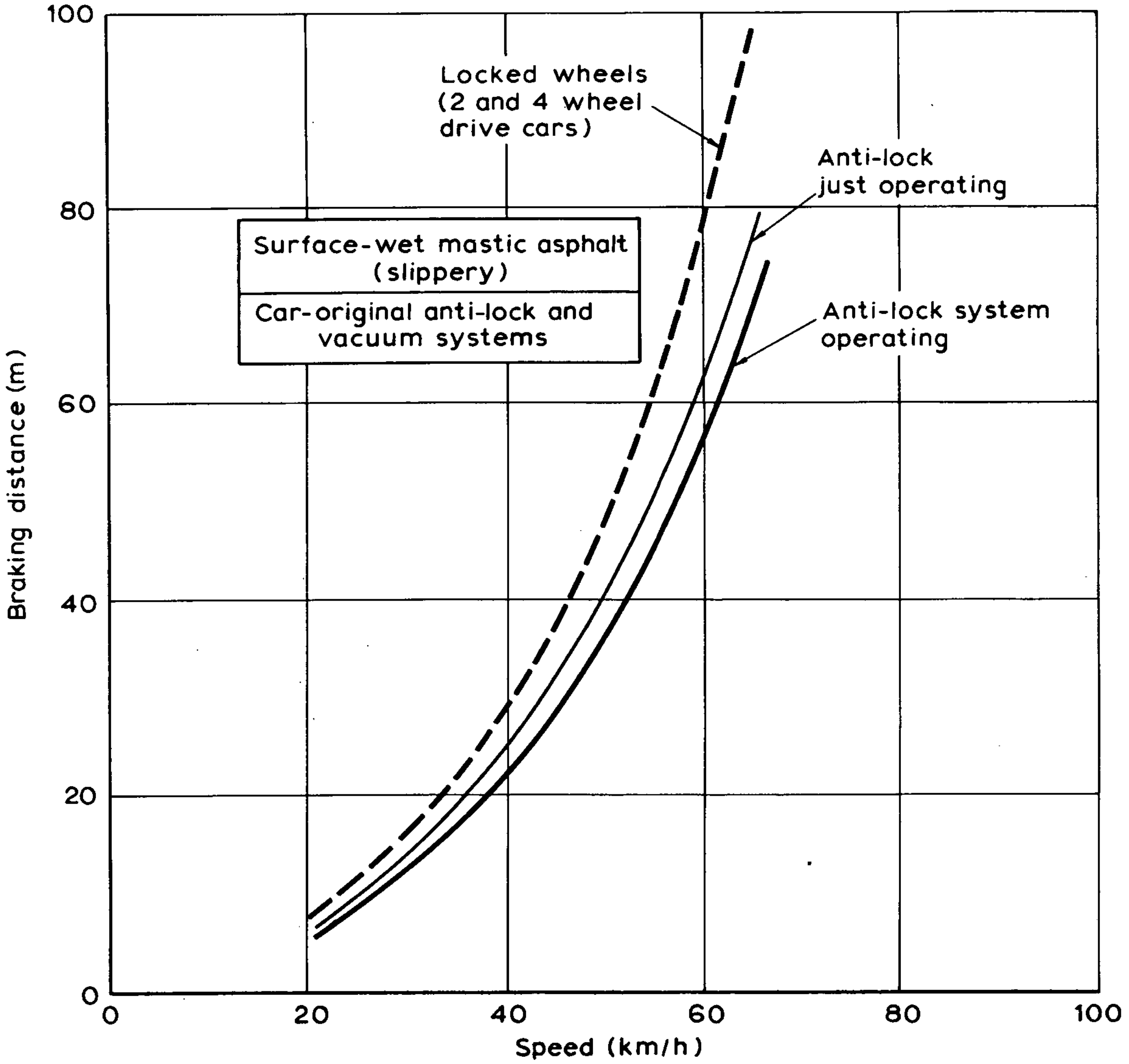


Fig. 2. BRAKING DISTANCES FROM DIFFERENT SPEEDS WITH AND WITHOUT ANTI-LOCK BRAKING OPERATING ON WET LOW RESISTANT SURFACE

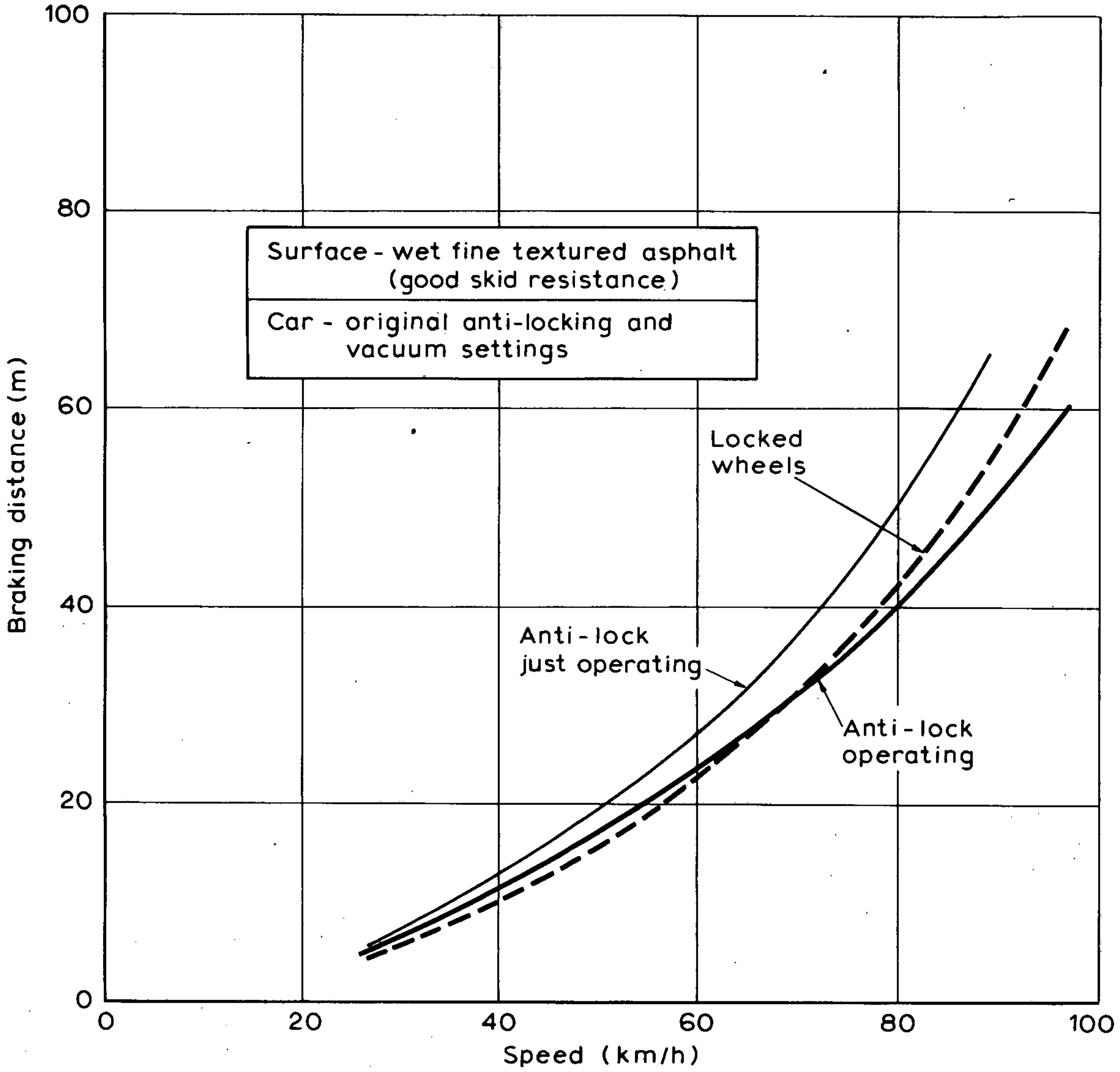


Fig. 3. BRAKING DISTANCES FROM DIFFERENT SPEEDS WITH AND WITHOUT ANTI-LOCK BRAKING SYSTEM OPERATING ON A WET GOOD SKID RESISTANT SURFACE

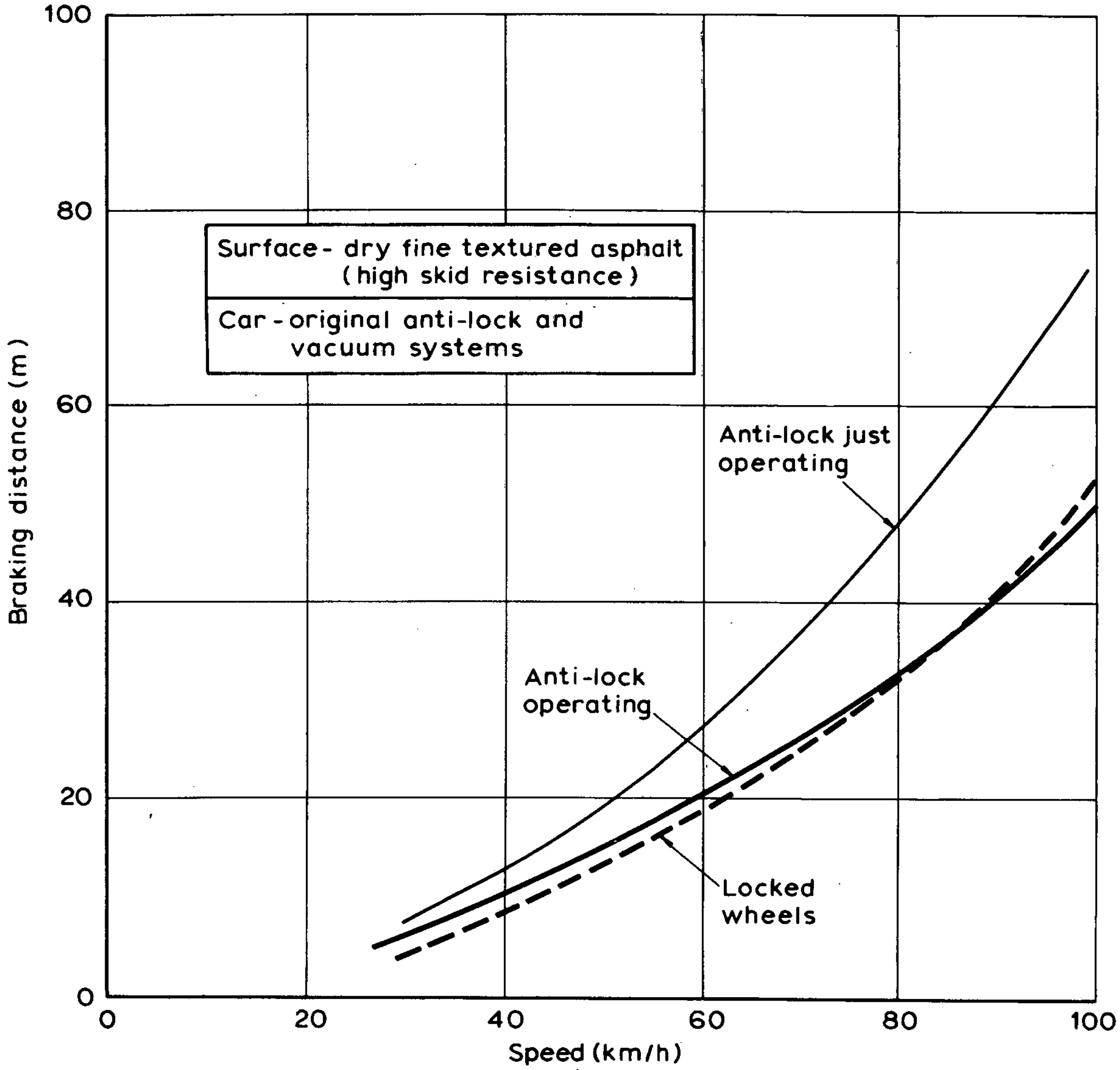


Fig. 4. BRAKING DISTANCES FROM DIFFERENT SPEEDS WITH AND WITHOUT ANTI-LOCK BRAKING SYSTEM OPERATING ON A DRY HIGH SKID RESISTANT SURFACE

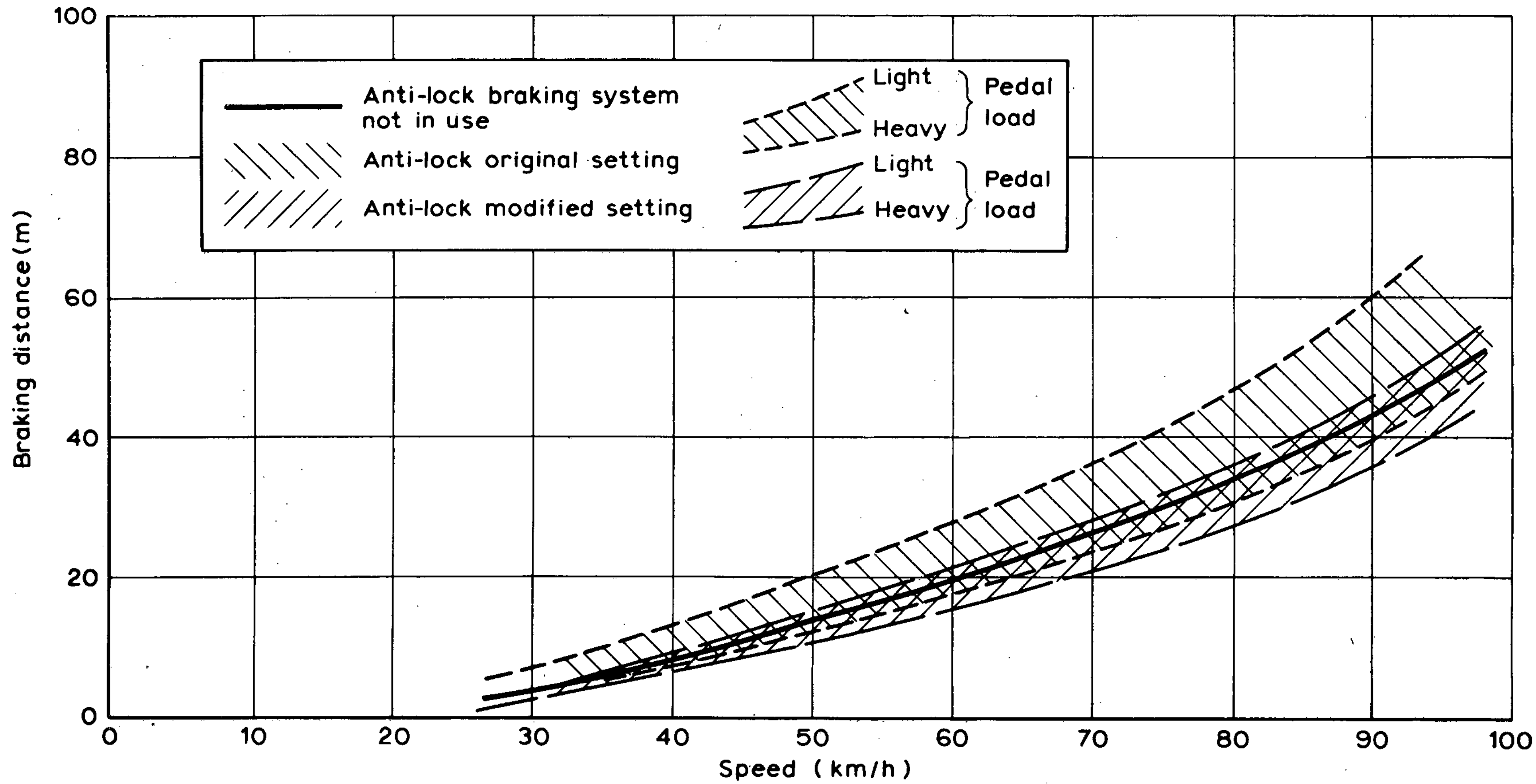


Fig. 5. BRAKING DISTANCES OBTAINED WITH ANTI-LOCK BRAKING SYSTEM IN USE AT INITIAL AND MODIFIED SETTING USING BOTH LIGHT AND HEAVY PEDAL EFFORT ON A DRY GOOD SKID RESISTANT SURFACE

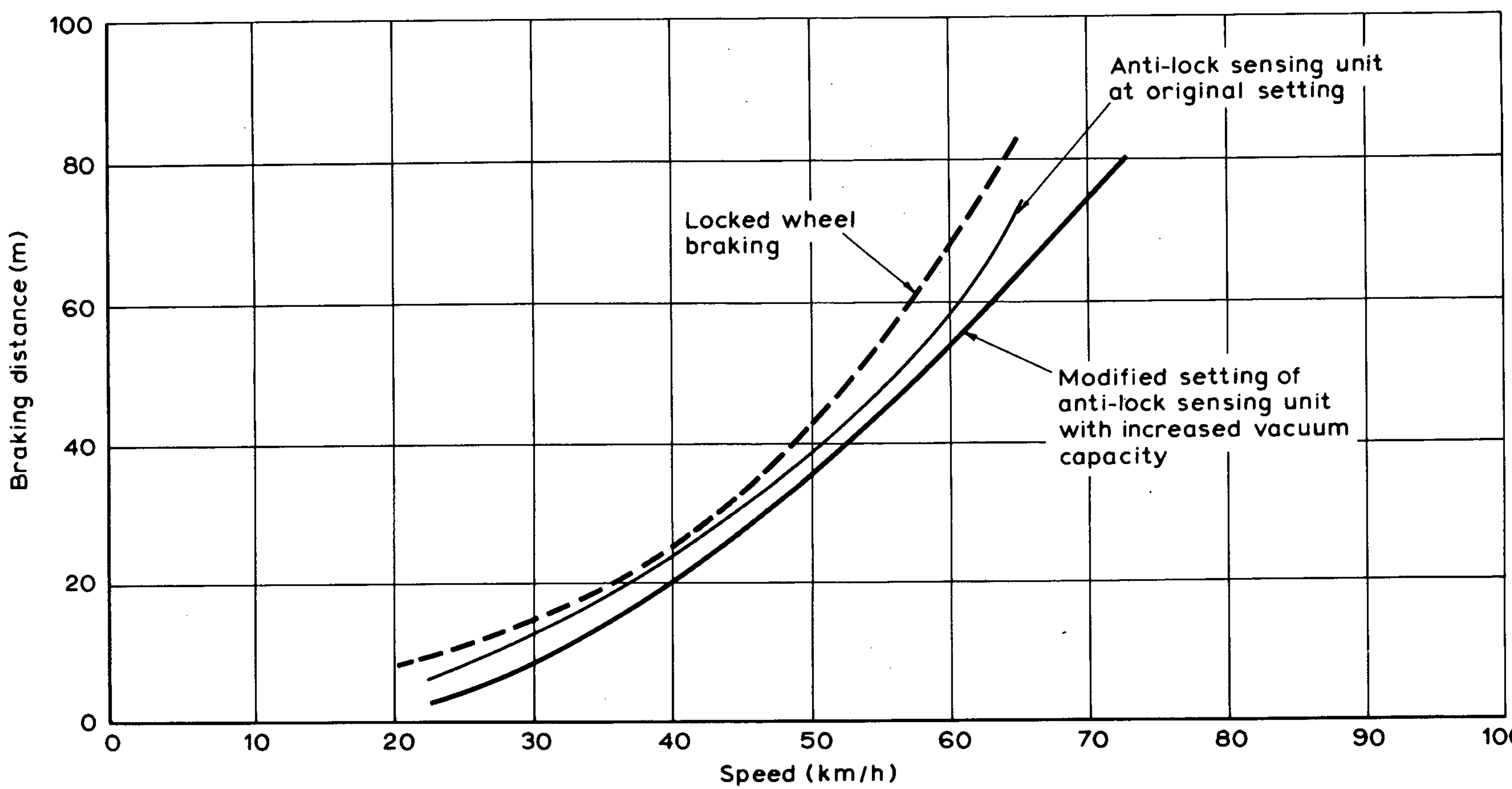


Fig. 6. BRAKING DISTANCES FROM DIFFERENT SPEEDS ON A WET SLIPPERY SURFACE

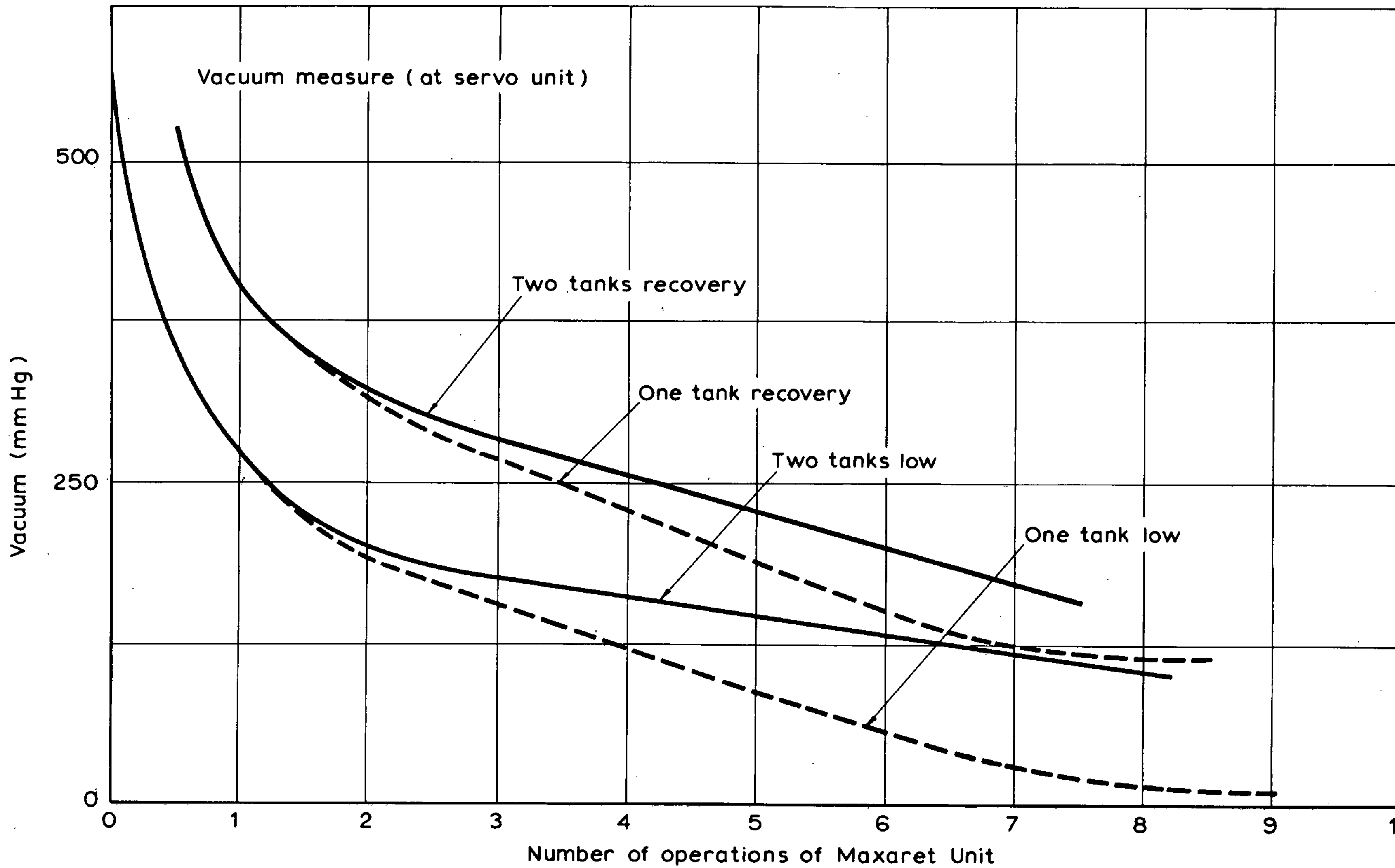


Fig. 7. REDUCTION IN VACUUM AT BRAKE SERVO UNIT WITH SUCCESSIVE OPERATIONS OF ANTI-LOCK BRAKING SYSTEM DURING ONE STOP ON A WET SLIPPERY SURFACE WITH ONE VACUUM RESERVOIR AND WITH TWO VACUUM RESERVOIRS

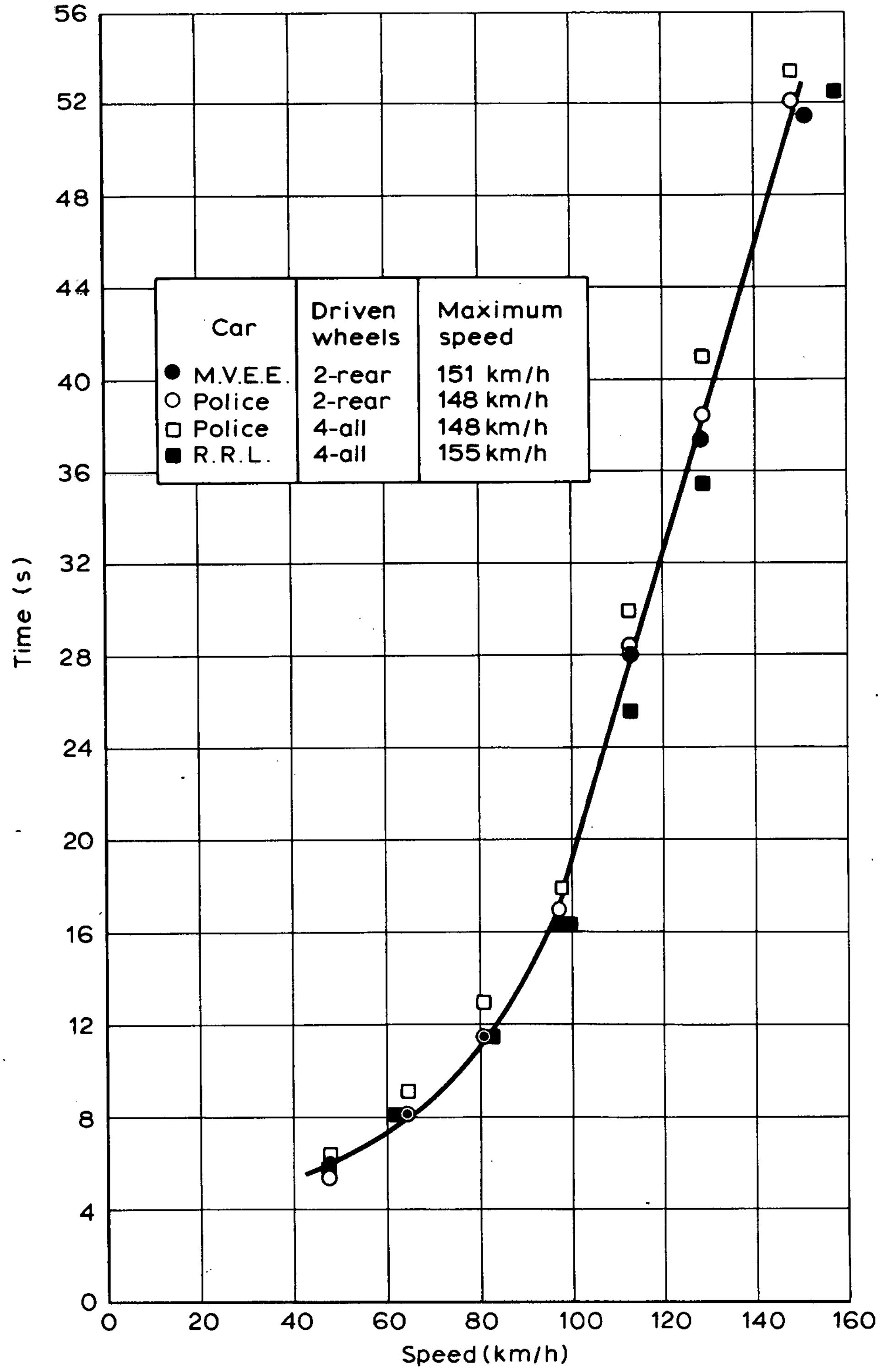
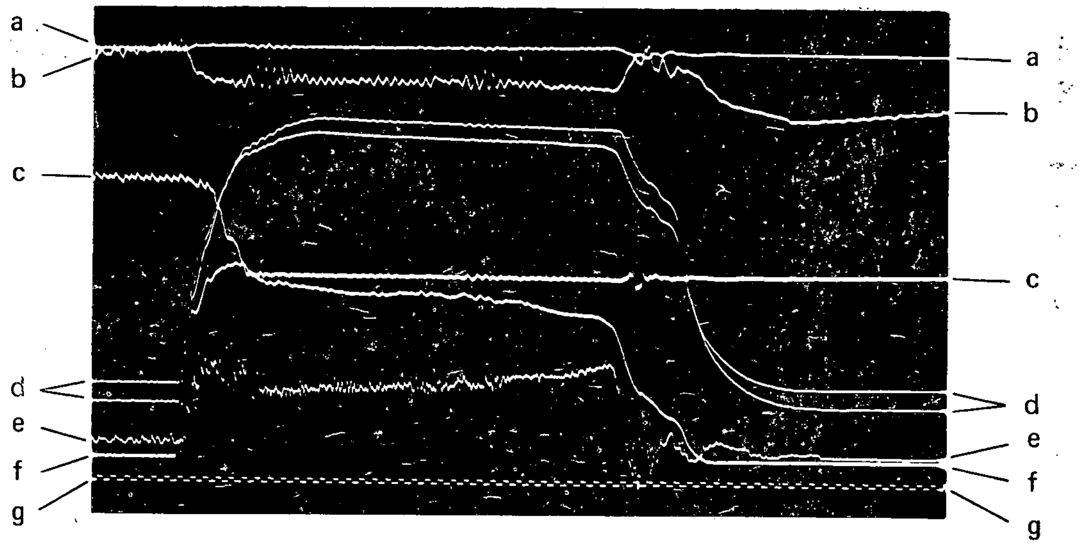
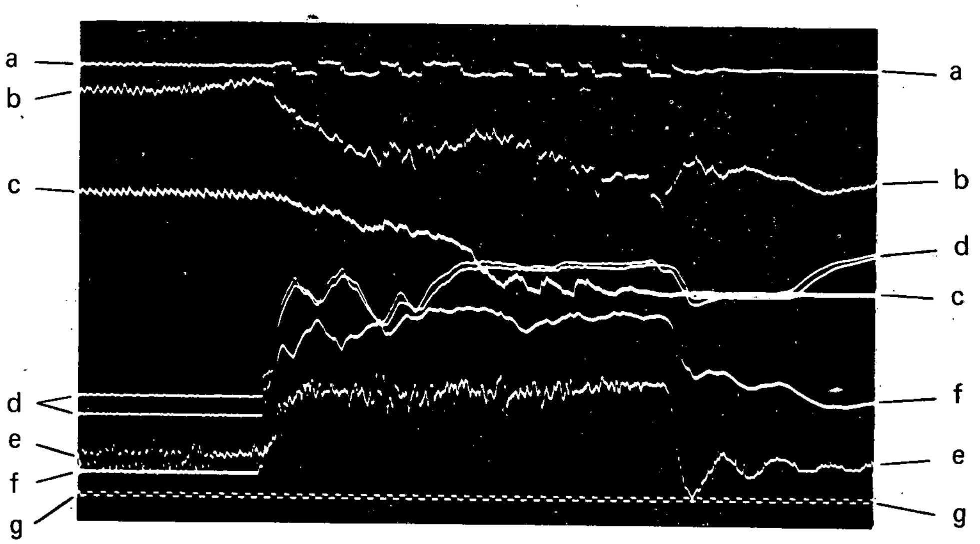


Fig. 8. TIME TAKEN TO ACCELERATE TO DIFFERENT SPEEDS BY FOUR AND TWO WHEEL DRIVE CARS



a. Locked wheel stop from 72 km/h
Braking distance = 32 m



b. Stop with anti wheel locking system from 72 km/h
Braking distance = 31 m

Key to traces

a = Operation of Maxaret Unit

b = Vacuum supply level

c = Rear propeller shaft speed

d = Front and rear brake line pressures

e = Car deceleration

f = Brake pedal application load

g = Timing trace

PLATE 1

Galvanometer records of emergency stops on a wet surface with a good skid resistance without and with the anti wheel locking system

(1144) Dd891796 3M 8/72 H P Ltd, So'ton G1915
PRINTED IN ENGLAND

ABSTRACT

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