EXPERIMENTAL INVESTIGATION IN VEHICLE PERFORMANCE AND RESPONSE DURING NOMINAL, RECTILINEAR BRAKING MANEUVERS

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Introduction

When a driver heavily brakes in attempting to avoid an accident, the vehicle does not always behave as expected. The front wheels may lock, in which case the car cannot be steered, the rear wheels may lock, in which case the car tend to slew round (1, 2). In such a situation, where the driver applies his brakes as hard and as rapidly as possible, it is vital to achieve the shortest stopping distance; but in attempting to do this, the driver may lose control of his vehicle rather than to shorten the stopping distance (3, 4). Studies of road accidents show that loss of control is a common feature (5).

This paper discusses the problems associated with vehicle performance and response during nominal, rectilinear (no-steer) braking maneuvers. The main purpose of this investigation is to study the effect of the following parameters on vehicle performance and response during braking:

a) wheels' locking time,
b) initial vehicle speed,
c) brake temperature,
d) braking oil pressure form (constant or pulsating).

Road tests were performed with a passenger car type Lada 1200, the car fitted with disc brakes at front and drum brakes at rear. The test car was subjected to straight-line braking tests on two pavement surfaces; dry and wet asphalt.

— Tests Procedure and Measurements

Tests started with speeds $U_0 = 30, 40, 60, 70$, and 80 km/h. Brake inputs of a quasi-step form were produced by slamming the brake pedal against adjustable stop (see Fig. 1). In a sequence of tests, for a given pavement condition (dry or wet), line pressure was increased in increments of approximately 1 MPa until a wheel lockup condition arose. Tests were run on a vehicle in full

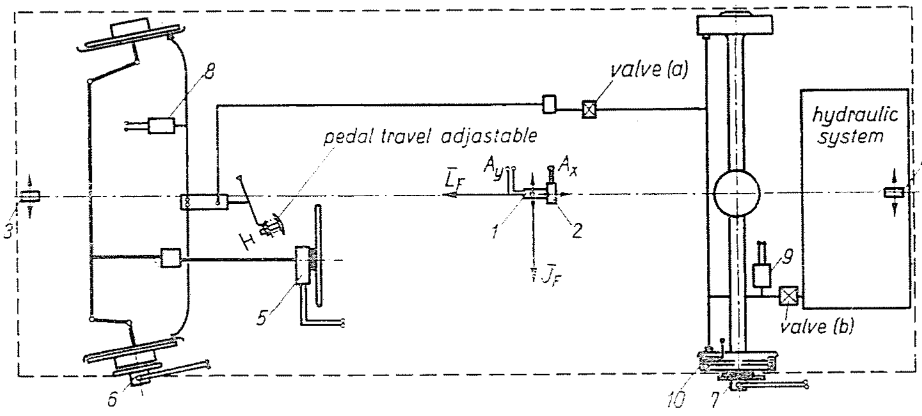


Fig. 1. Measurement arrangement

load condition (driver, test operator, instrumentation package, plus hydraulic brake system). This additional loading resulted in front-to-rear mass distribution of 669 kg/661 kg.

The investigation may be subdivided into three parts:

1. Braking with only front wheels.
2. Braking with front and rear wheels.
3. Braking with front and rear wheels by applying pulsating braking oil pressure.

The applied measuring arrangement is shown in Fig. 1, where the following parameters were measured:

a — Vehicle longitudinal deceleration was measured by accelerometer (2g), located close to the vehicle center of gravity (1).

b — Vehicle lateral accelerations were measured by three accelerometers; the first located close to the vehicle center of gravity; the second located at the front extreme point; and the third located at the rear extreme point (2, 3 and 4, resp.).

c — Steer wheel angle was measured by means of a pot-meter (5).

d — wheel angular speeds were measured byelec tronic indicators installed on both left wheels (6, 7).

e — Brake line pressures were measured by strain gauge pressure transducers (8, 9).

f — Rear left brake lining temperature was measured by thermocouples installed in brake lining (10).

The measured parameters were recorded by a fourteen-channel light-beam oscillograph, Fig. 2. shows the instrumentation in the test car.

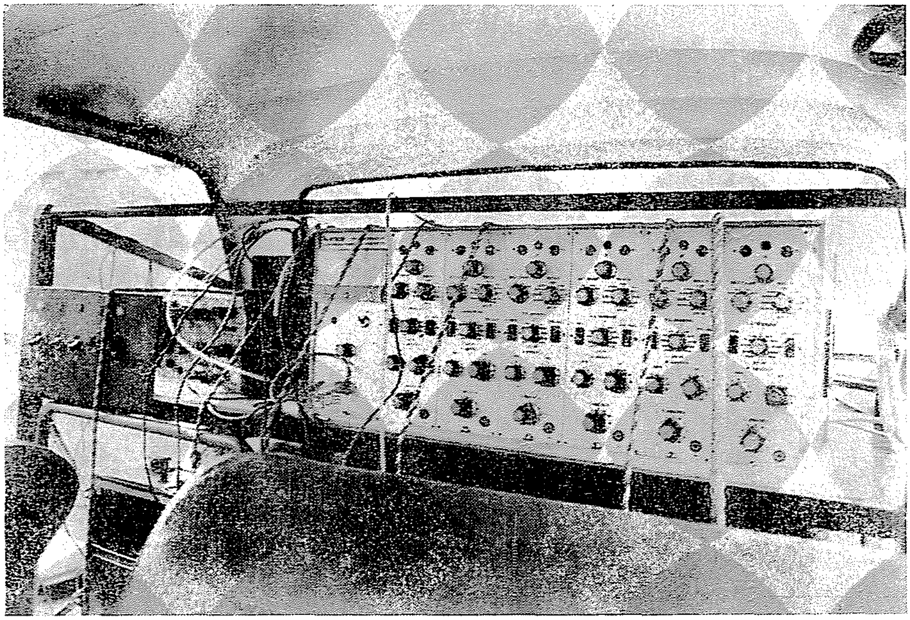


Fig. 2. Instrumentation in the experimental car

— Braking with Only Front Wheels

It has been shown by J. L. HARNED (4) and R. LIMPERT (6) that the braking force coefficient is greatest at a particular value of slip between tyre and road; this value is about 20 per cent, but the precise figure is not well established and probably depends on both tyre and road properties. Therefore, in applying the brakes of a car so as to lock the wheels, the following sequence of events takes place: at the instant when pressure is applied to the brake pedal the wheels are rotating freely, the slip is zero and, of course, the braking force is zero, too; as the pressure is increased the slip increases until at some critical value the braking force reaches a maximum (peak deceleration); if the slip increases still further the braking force decreases until finally the wheels lock (locked deceleration), when, of course, the slip is 100 per cent.

The peak deceleration is not always easy to demonstrate when braking on all four wheels, since in practice it is difficult to obtain a condition of impending skid simultaneously at all four wheels, at a given moment each wheel or pair of wheels usually having a different percentage of slip. For this reason, and to demonstrate the peak deceleration, which is important in this part of the investigation, braking with front wheels only was carried out by closing valve (a) (see Fig. 1).

Some deceleration time records, given in Fig. 3. (a and b), for a vehicle with only the front wheels braked and locked, cover the whole sequence from

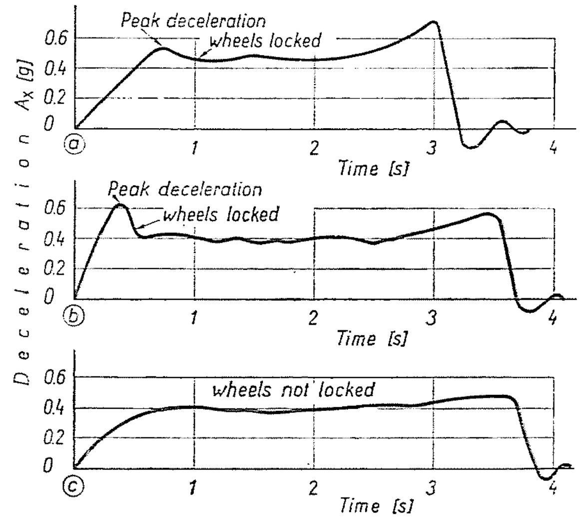


Fig. 3. Deceleration/time curves in braking with front wheels alone

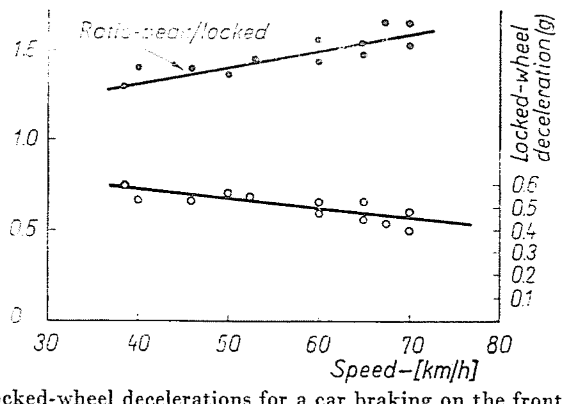


Fig. 4. Peak and locked-wheel decelerations for a car braking on the front wheels alone, from different speeds on dry asphalt surface

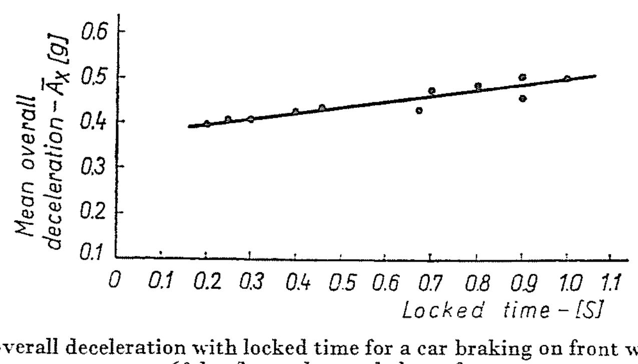


Fig. 5. Mean overall deceleration with locked time for a car braking on front wheels alone, from 60 km/h, on dry asphalt surface

rolling to sliding, and show a fairly pronounced peak corresponding to the maximum value of the braking force coefficient just before the wheels lock. Fig. 3 c shows deceleration/time record of braking, in which the wheels did not lock, failed to show this peak, but the braking force may have been below that for locked wheels.

The results for dry asphalt surface tests are given in Fig. 4, where the peak and locked-wheel decelerations are expressed as a ratio. On this surface the peak deceleration was found to be nearly 1.7 times that of the locked-wheel deceleration at a speed of about 70 km/h.

The effect of the wheels lockup timing on the mean overall deceleration (braking performance) was investigated at a speed of about 60 km/h. The obtained results are given in Fig. 5, where the vehicle mean overall deceleration is plotted versus wheels lockup time. It was found that the mean overall deceleration at 1 s lockup time is about 1.25 times that at 0.2 s lockup time.

The results obtained indicate the potential value of the braking control systems when applied to cars, to improve the locking time.

— **Braking with all wheels**

Tests were run on vehicle subjected to straight-line braking (zero steer wheel angle) on two pavement surfaces: dry and wet asphalt, brakes applied on all wheels.

During the tests the vehicle was subjected to disturbance from winds, transverse slop of road surface, and from other many causes, for this reason the tests started with a low speed ($u_0 = 25$ km/h), increased in increments of approximately 10 km/h. It should be noted that the tests were carried out by applying constant pressure of brake oil, and the time required to reach the maximum value of pressure was within 0.2—0.3 s. The maximum speed approached during the tests was 80 km/h. Fig. 6 shows typical recording for straight-line braking tests on dry asphalt at a speed $u_0 = 80$ km/h.

Braking effectiveness determined from straight-line braking tests is given in Fig. 7, where the mean overall deceleration $\bar{A}_x$ is plotted versus the brake oil line pressure P_l at different vehicle speeds ($U_0 = 40$ and 70 km/h). The maximum value of the deceleration for dry surface is seen to occur at a line pressure of about 8.5 MP_a and for wet surface, at a line pressure of 5.5 MP_a. It is also clear that the deceleration decreases if the line pressure increases more than the value where the maximum deceleration occurred. The main reason of this degradation in deceleration is related to the lock-up time of wheels (see Fig. 5).

Effect of vehicle speed on the deceleration was investigated, and show in Fig. 8. The deceleration is seen to decrease as the speed increases, attributed to the effect of the wheel sliding speeds and slip-ratios on the coefficient of friction at the tyre-road interface (7).

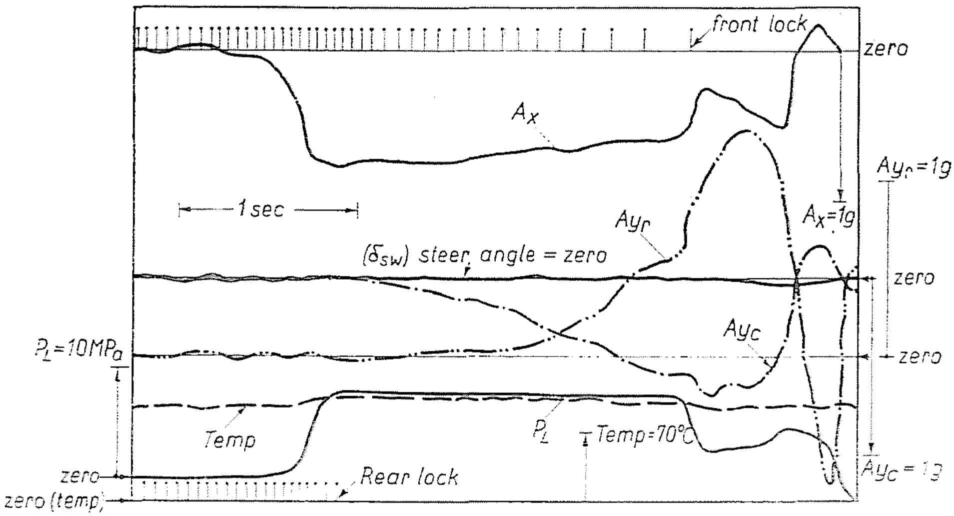


Fig. 6. Typical records in a straight-line braking test (dry asphalt, 80 km/h)

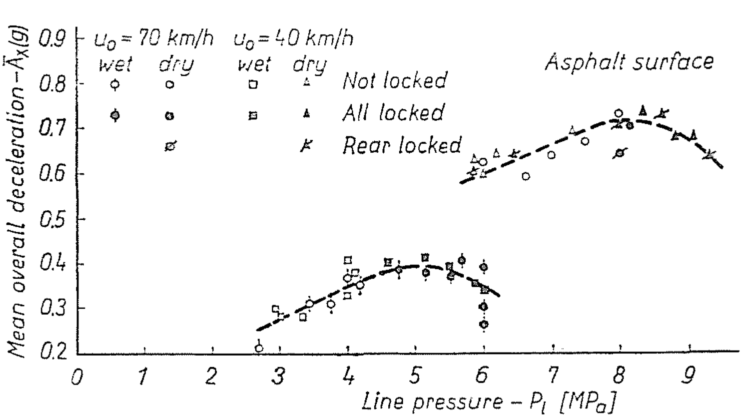


Fig. 7. Braking effectiveness determined from straight-line braking tests

In this investigation braking was applied as rapidly as possible (such as emergency braking). In such a kind of braking it was found that the brake temperature plays an important role in improving the braking effectiveness and vehicle response, where braking at relatively high temperature of the rear brakes (shoe brakes) improves the lockup time of wheels (see Fig. 9); this improvement is limited by the temperature at which complete fade of brakes occurred, and then the braking torque tended to zero, of course, this is an undesirable condition (8).

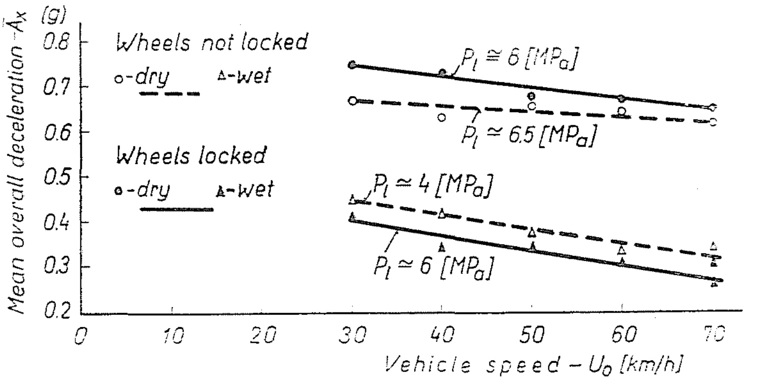


Fig. 8. Mean overall deceleration versus vehicle speed

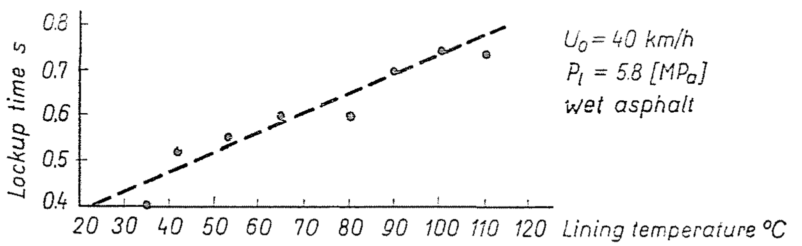


Fig. 9. Lockup time versus lining temperature

In the effectiveness tests the directional responses produced were measured. The vehicle directional responses were expressed in terms of maximum yaw and lateral accelerations. Two methods were employed in order to calculate the yaw acceleration, such as:

1 — Direct measuring of the lateral acceleration difference produced, by means of accelerometers fixed at rear and front (see Fig. 1), then the yaw acceleration can be calculated as:

$$\ddot{\varepsilon} = \frac{\Delta A_y}{l_a} \tag{1}$$

where:

ΔA_y = Measured lateral acceleration difference
l_a = distance between the accelerometers.

2 — Measuring of both lateral accelerations at the vehicle center of gravity and at the rear extreme point, the yaw acceleration can be calculated as:

$$\ddot{\varepsilon} = \frac{A_{yc} - A_{yr}}{l_{rc}} \tag{2}$$

where:
A_{yc} = lateral acceleration at vehicle center of gravity;

A_{yr} = lateral acceleration at rear extreme point;
l_{rc} = distance between the accelerometers.

Both methods were utilized, and the second method was found to be more accurate than the first one.

Many factors were found, however, to affect the vehicle behaviour or response during braking, such as lockup time of rear wheels, initial vehicle speed, road coefficient of friction and tyre characteristics.

All of the factors affecting the vehicle response were found to be expressed by a number n_c the so called 'Critical Response Number', expressed as follows:

$$\eta_c = \frac{t_s - t_{sr}}{t_s} \tag{3}$$

where
t_s = vehicle stopping time,
t_{sr} = rear wheels lockup time.

Fig. 10 shows the number n_c versus the absolute maximum lateral acceleration A_{ycmax} and the absolute maximum yaw acceleration $\ddot{\varepsilon}_{max}$, the absolute values were utilized because they may be positive or negative. In Fig. 10, dramatical loss of directional stability is seen at $\eta_c > 0.6$, it is also clear that for safety reasons the number η_c must not be greater than 0.3. This number is valid only if the rear wheels locked before the front ones, or if the slip-ratio of the rear wheels is greater than that of the front ones, $S_R > S_F$.

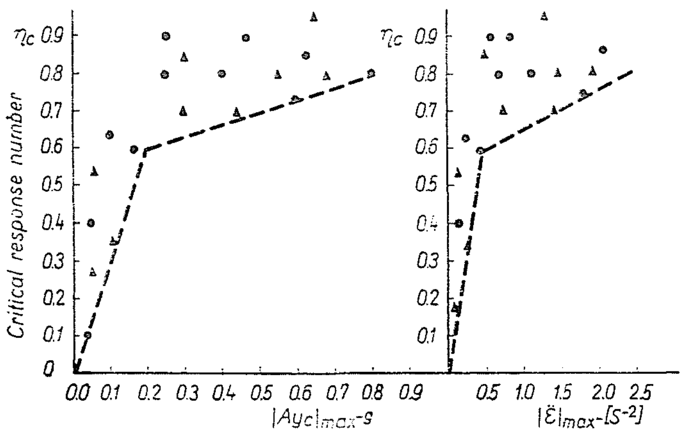
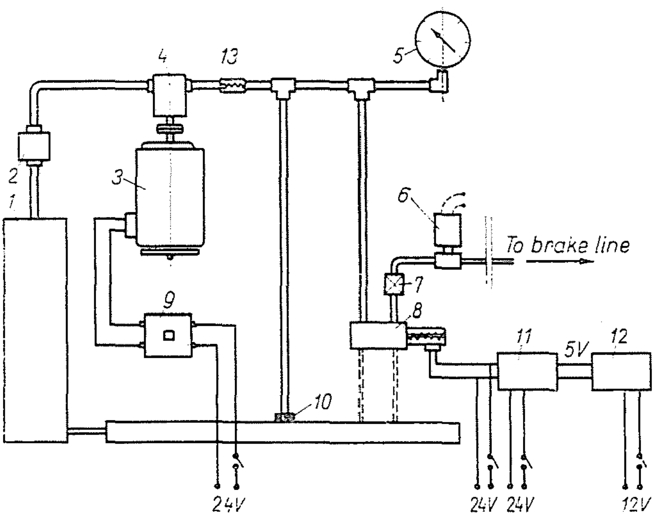


Fig. 10. Critical response number versus vehicle maximum lateral and yaw accelerations

— Braking with Applied Pulsating Line Pressure

An important conclusion of the above tests results is that the sensing proportioning valve fitted into the vehicle brake system cannot prevent rear wheels from locking, which produced dramatical loss of directional stability and braking effectiveness. The investigated vehicle brake system is fitted with a sensing valve (open loop control), which senses load at the rear axle only by measuring suspension deflection. The sensing valve failed to prevent locking because the principle of open loop control is subject to a number of errors. One of the first assumptions made is that the brake torque is proportional to the brake line pressure, since it is the brake line pressure which is controlled. Brake sensitivity, particularly with drum type brakes, is known to considerably vary particularly with fade induced by hard usage. The second assumption is that the tyre-to-road friction coefficient is the same for all four tyres. This may not be true due to local differences in the pavement surface or differences in the tyres or operating conditions. For example, the use of studded or snow tyres on the rear wheels can much change the desired brake torque distribution. Similarly, when running in deep water, the rear tyres operate in the cleared path of the front wheels and, therefore, have different friction characteristics. All of these factors limit the accuracy of open loop brake proportioning schemes.

The inherent limitations of brake proportioning schemes can be partially solved by using antilock device (close loop controller). But the current antilock systems are very complex and expensive. Therefore it is impossible, from the point of view of vehicle cost, to use an antilock system in each car.



No	Denomination
1	Brake oil tank
2	Oil filter
3	24 V, DC motor
4	Oil pump
5	Pressure gauge
6	Strain gauge pressure transducer
7	Valve
8	Pulsator
9	Motor relay
10	Maximum pressure control orifice
11	Electronic pulsator
12	5 V generator and stabiliser

Fig. 11. Braking actuating and pulsating system

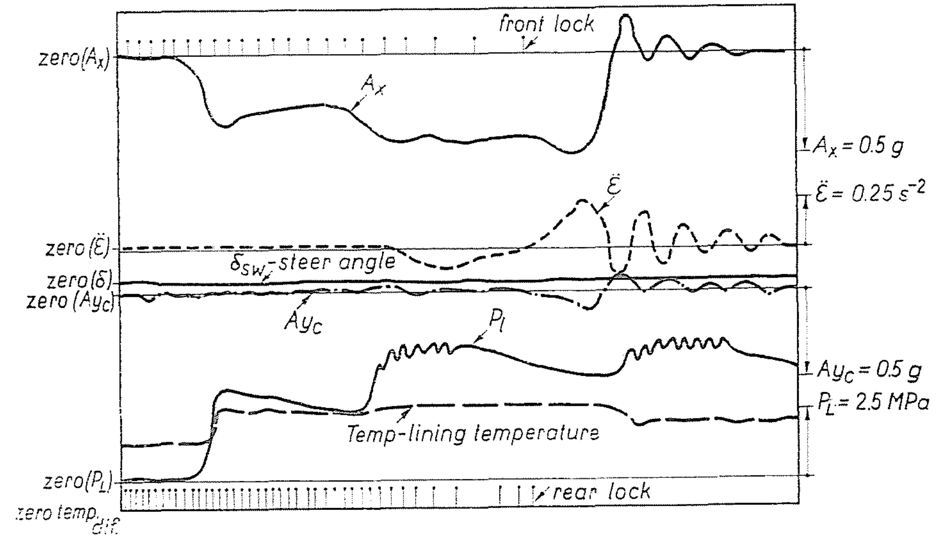


Fig. 12. Typical records in a straight-line braking test by using pulsating braking pressure (wet asphalt, 40 km/h)

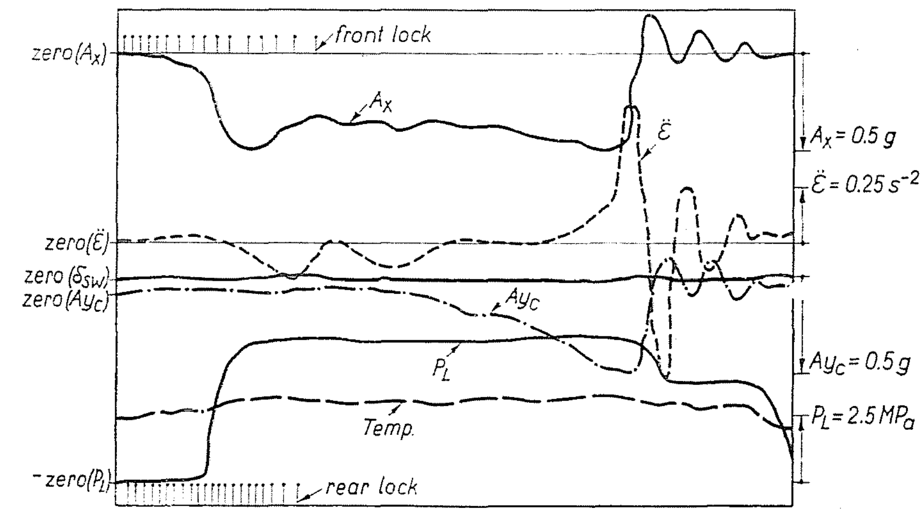


Fig. 13. Typical records in a straight-line braking test applying constant braking pressure (wet asphalt, 40 km/h)

Due to the inherent factors the concept of pulsating braking pressure has been used, where the concept relies on pulsating oil pressure on all wheels, without removing the sensing valve. The pulsating pressure has two benefits, the first one is to improve the locking time of front wheels (controllability), the second one is to avoid quick locking of rear wheels when sensing valve cannot control the oil pressure at rear wheels, as illustrated before.

First application of pulsating braking pressure was performed by J. GRABOWSKI (9). His study was restricted to air-brake systems, and applied the pulsating torque on rear wheels alone, without any attention to locking of front wheels.

However, in this investigation a hydraulic system was designed to generate pulsating pressure to all wheels, the pulse frequency was controlled by an electronic control system (see Fig. 11).

Fig 12 and 13 show typical recording in the straight-line braking test by using the vehicle brake system and the pulsating brake system.

Fig 12 and 13 clearly show the advantage of braking by pulsating pressure. The locking time of both front and rear wheels is seen to improve, resulting in better vehicle response Ay_c and $\ddot{\varepsilon}$ and controllability (front wheels did not lock untimely).

Summary

The present investigation concerned problems associated with vehicle performance and response during straight-line braking. Effects of wheel locking time, vehicle speed, and line pressure on braking effectiveness expressed, by vehicle mean overall deceleration $\overline{A}_x$, and vehicle response, expressed by lateral and yaw acceleration Ay_c and $\ddot{\varepsilon}$, respectively, were investigated. Test results showed that the vehicle response and braking effectiveness was highly affected by timing of wheel locking, and also influenced by the brake temperature.

A new number, the so-called critical response number η_c, was introduced, expressing the effect of rear wheel locking on the vehicle response. For $\eta_c \geq 0.6$ dramatic loss of directional stability was observed. For safety causes it is recommended that the number is not greater than 0.2.

The concept of pulsating braking was investigated. Results showed that using pulsating pressure during braking may improve the locking time of both front and rear wheels.

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