QUALITATIVE ANALYSIS ON THE VAPOR LOCKING VEHICLE BRAKE SYSTEMS

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1. INTRODUCTION

Various problems in understanding skidmarks left on the road surface have been clarified by recent study of the skidmarks, so abnormal car movements and the driving state at a road accident may be estimated from many kinds of skidmarks patterns. But we still can not explain the origins of all kinds of skidmark. For example, the faint one left on micro coarse textures both by a passenger car which has no brake fluid pressure control valve for wheel lock prevention, and by the emergency braking of a driver's brake pedal operation. On the other hand, the frictional coefficients of organic materials for braking (for example, disk brake pads and drum brake linings) generally decrease according to the temperature rise in the brake system. An increase in the brake system-temperature makes the brake fluid temperature rise and results in generating bubbles in the brake tube, disk calliper and brake cylinder. In this case, an expected line pressure can not be achieved in the system.

Many of the brake fluids used in the cars are almost non petroleum oil and are water soluble, so the lowering of the boiling point can not be avoided by their hygroscopicities. The brake fluids used in some kinds of motor vehicle contain ca. 10% water by volume, with a very low boiling point. In this case the vapor lock phenomenon may easily occur.

In many recent studies, a relation between vehicle braking deceleration decrease and, heat fade and vapor lock phenomena have been investigated in detail. But the initial state of those phenomena has not been picked up as a theme of research. We have studied the relation between skidmarks and the initial state of heat fade and vapor lock phenomena, one of the instability of braking device effect, paying special attention to the temporary decrease of braking force, in other words, the temporary braking wheels-unlock phenomena.

For those studies we carried out some emergency braking tests using a passenger car and heating tests of braking fluid in order to know the possibility of generating the heat fade and vapor lock phenomena, the relationship between water content in the braking fluid and those phenomena, and the relationship between braking system-line pressure, brake fluid temperature and master cylinder-push rod travel in the braking system of the tester.

2. EXPERIMENTAL METHOD.

The following four experiments were carried out : three braking tests (1), (2), (3) and a high temperature test of brake fluid.

2-1. Braking test (1).

In order to learn the possibility of generating the heat fade and vapor lock phenomena, straight emergency braking tests were carried out using a passenger car, Nissan Cedric®, which was produced in 1974 and equipped with a front disk brake device and a rear drum brake device. For this test we utilized brake fluid whose boiling point is ca. 116°C (389°K). This fluid is a mixture of new non-petroleum braking fluid, which is completely miscible with water and initially contains ca. 0.3% water by volume, and distilled water.

In this test the initial speed of braking was ca. 50-60km/h (13.9-16.7m/s), and measuring block diagram for this test is shown in Fig. 1. Braking pedal effort were added by the apparatus shown in Fig. 2. It consists of an air cylinder (0.032ϕ × 0.15m), air tank (volume : 30l (0.03m^3), maximum allowable pressure : 9kgf/cm^2 (8.8 × 10^5 Pa)), pressure regurator valve and electromagnetic valve etc.. When the air tank is filled, it is possible to operate the vehicle braking system about 200 times. In this test, the air pressure for the air cylinder operation was constant and at 2.5kgf/cm^2 (2.5 × 10^5 Pa), so the pedal effort is ca. 20kgf (196N). In this experimental condition, the maximum

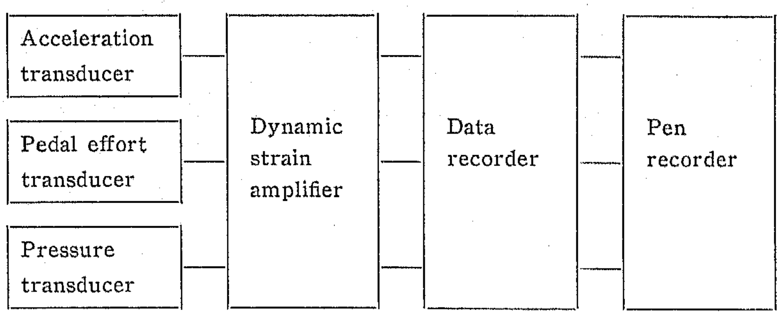

Fig. 1 Measuring block diagram for braking test (1).

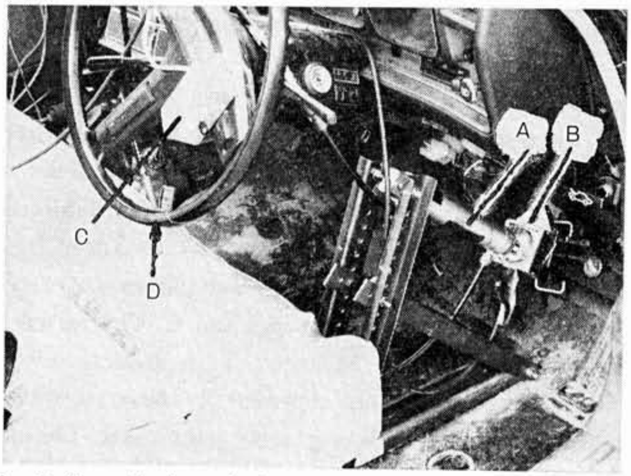

Fig. 2 Overall view of the apparatus for brake pedal effort.
A : Air cylinder (32ϕ × 150mm).
B : Brake pedal effort transducer (capacity : 100kgf).
C : Switch for electromagnetic valve operation.
D : Steering wheel.

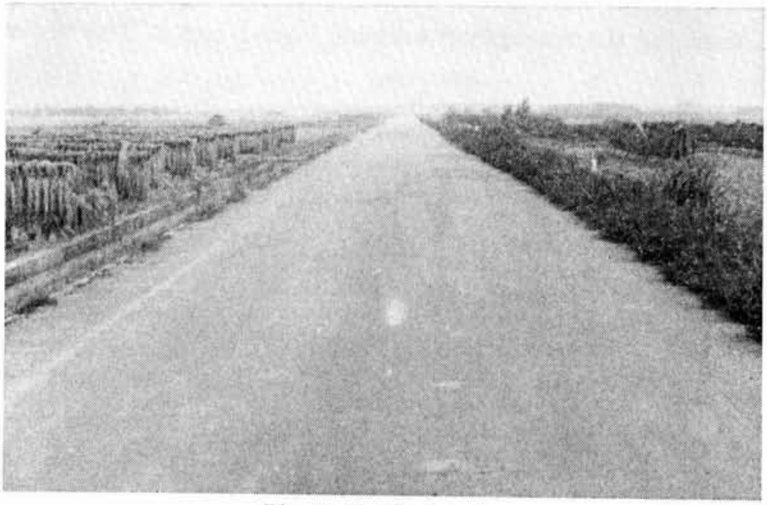

Fig. 3 Testing road.

braking deceleration gained in the tests was ca. 0.7g (g : the acceleration of gravity) and the wheel lock phenomenon did not occur.

This braking test was continuously repeated on the straight road shown in Fig. 3, until braking deceleration was greatly decreased. The interval of time between the start of a braking test and the start of the following one is ca. 10-20 seconds. Ambient temperature during these tests was ca. 14°C (287°K).

2-2. Braking test (2).

In order to learn the relationship between heat fade and vapor lock phenomena and the brake fluid boiling point, braking tests were carried out in the same way as test 1. In this test, the brake fluid temperature in the front disk calliper of the right hand side was measured by the thermocouples. The position of the thermocouple installation and measuring block diagram for this test are shown in Figs. 4, 5 and 6. The initial speed of the braking was ca. 70-80km/h (19.4-22.2m/s). This braking test was, in the same manner as test 1, continuously repeated on the straight road shown in Fig. 3 until braking deceleration was greatly decreased. The ambient temperature during this test was ca. 26°C (299°K).

2-3. High temperature test of brake fluid.

In order to learn the relationship between brake fluid temperature, master cylinder-push rod travel and line pressure, high temperature tests of braking fluid were carried out. The test apparatus is shown in Figs. 7, 8 and the measuring block diagram in Fig. 9. The brake master cylinder and the brake pedal for this experimental apparatus were of the same type as the one used for the emergency braking tests 1 and 2. The vessel shown

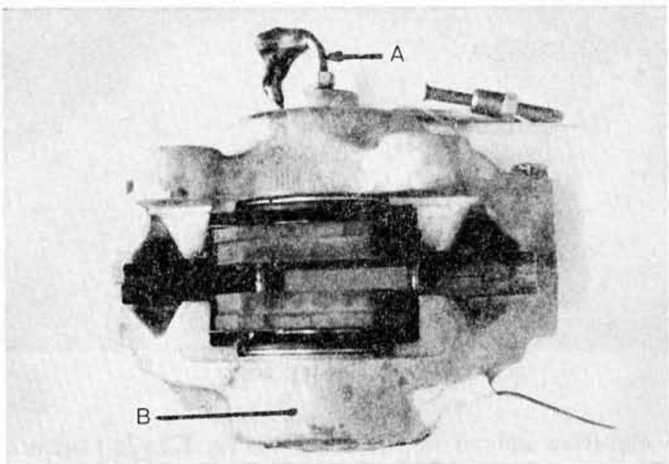

Fig. 4 Overall view of the calliper.
A : Brake tube.
B : Cylinder body of the outer piston.

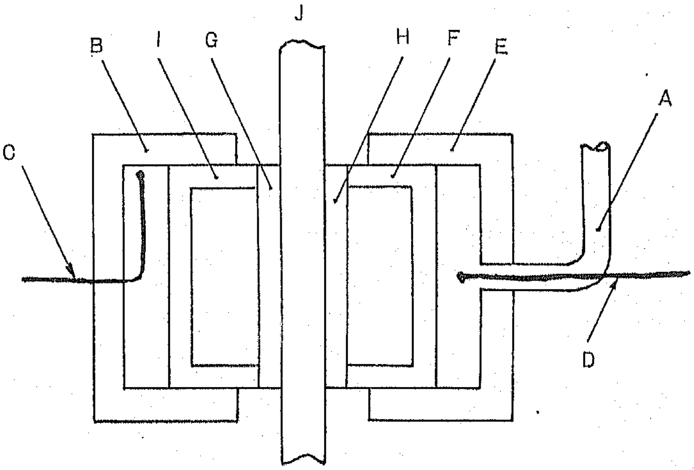

Fig. 5 Schematic diagram of thermocouple installation in the calliper.
A : Brake tube.
B : Cylinder body of the outer piston.
C, D : Thermocouple.
E : Cylinder body of the inner piston.
F : Inner piston.
G, H : Disk pad.
I : Outer piston.
J : Disk.

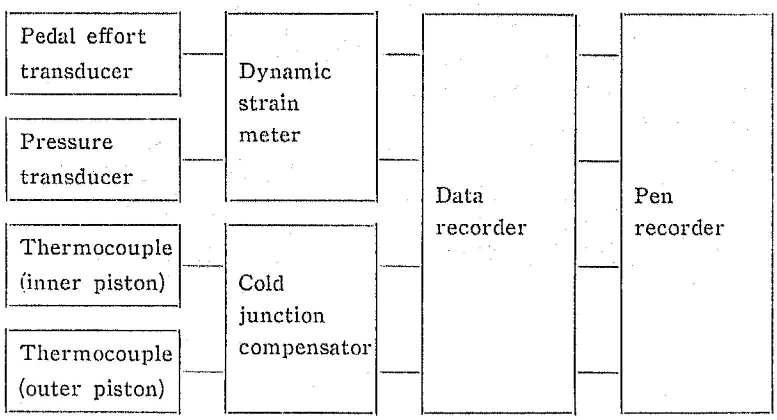

Fig. 6 Measuring block diagram of the braking test (2).

as vessel-**G** in Fig. 8 has a volume of 50cc (50×10^{-6} m^3), which is about twice as much as one of the disk calliper. The brake fluid in the vessel was heated indirectly by heating oil in which the vessel was soaked, with 300 W heater. The tests in this section consists of two types. The one in which the brake

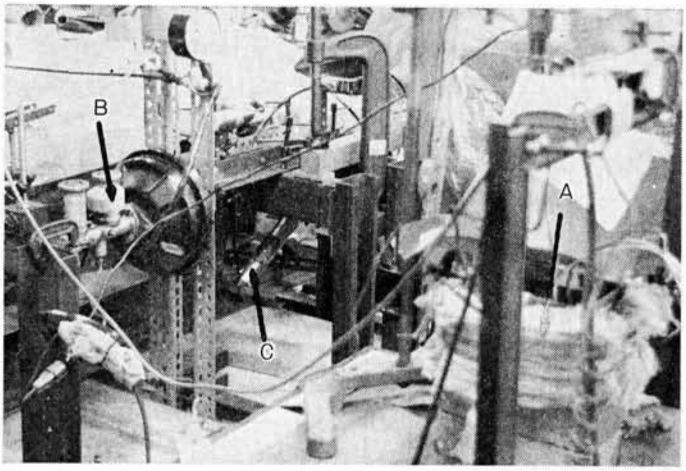

Fig. 7 Overall view of the equipment for high temperature test.
A : Heating vessel for brake fluid.
B : Master cylinder.
C : Air cylinder for pedal effort.

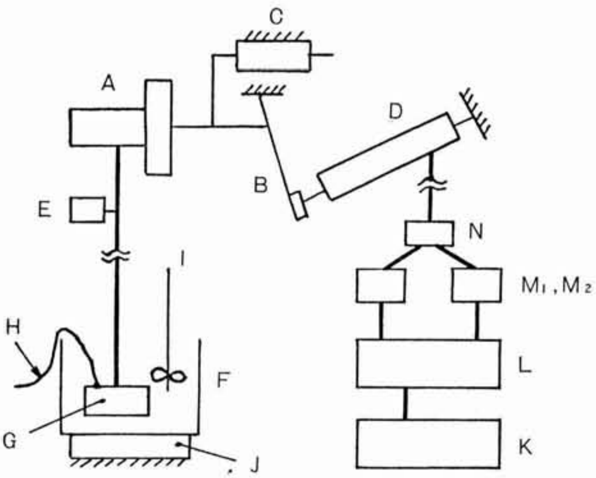

Fig. 8 Schematic diagram of brake fluid high temperature test.

A : Brake master cylinder.
B : Brake pedal.
C : Displacement trnsducer.
D : Air cylinder.
E : Pressure transducer.
F : Heating vessel.
G : Vessel-G.
H : Thermocouple.
I : Stirrer.
J : Heater.
K : Compressor.
L : Air tank.
$M_{1,2}$: Electromagnetic valve.
N : Shuttle valve.

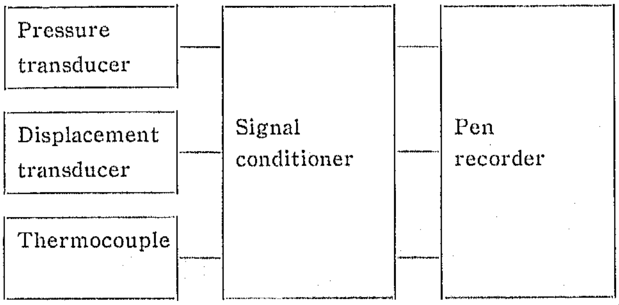

Fig. 9 Measuring block diagrm of high temperature test.

fluid was pressurized at an arbitary constant pedal effort : for example 50 kgf (490 N) in the first 5 seconds, and left with no pressurization in the following 55 seconds in the heated oil. These tests were repeated periodically until the brake master cylinder-push rod reserve was nearly equal to zero. This test was performed with 10 kinds of water content by volume in the brake fluid. The other type of test involved the repeated pressurization of the brake fluid in the same way described above. In this case, the pedal effort was 32 kgf (314 N). And when the brake fluid temperature became nearly equal to the boiling point, and the push rod travel became large, we adjusted the pedal effort from 32 kgf (314 N) to 40 kgf (392 N) for the following tests.

2-4. Braking test (3).

In order to learn the possibility of generating the heat fade and vapor lock phenomena, emergency braking tests were carried out using the same passenger car used in braking tests 1 and 2. At the beginning of this test, the pedal effort was ca. 25 kgf (245 N) and the initial speed of braking was ca. 50km/h (13.9m/s). The result was that the maximum deceleration of the tester was ca. 0.75*g* and some or all wheels were locked during braking. And when the braking wheels did not lock, the pedal effort was increased to 50 kgf (490 N) for the follwing braking tests. The ambient temperature during these tests was ca. 5°C (278°K).

3. EXPERIMENTAL RESULTS AND DISCUSSIONS.

3-1. Braking test (1).

An example of the test results is shown in Fig. 10. In this Figure **A**, **B** represent line pressure and braking deceleration respectively. There is no major change in deceleration and line pressure from the first braking test to the 40th one, shown as **a** in Fig. 10. After point **a**, the braking deceleration decreased in spite of no reduction of line pressure. In general, we can

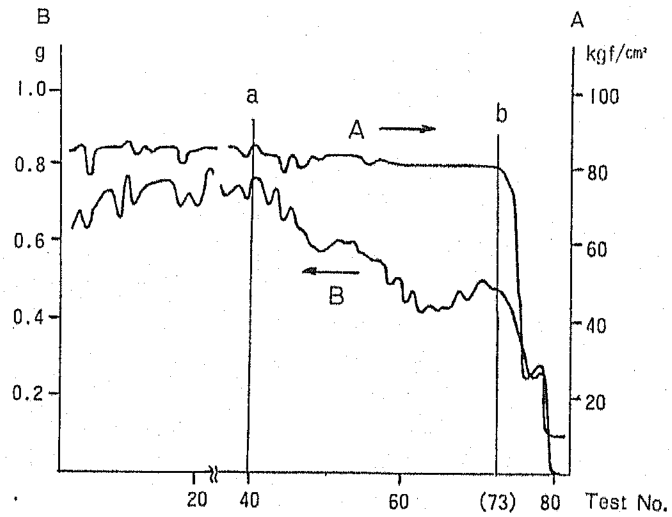

Fig. 10 An example of braking test (1) results.
A : Line pressure.
B : Braking deceleration.

give expression to this phenomenon as "the beginning of heat fade". A braking deceleration-decrease may occur by heat fade even if the water content in the brake fluid is smaller than in this case. But we can not confirm that the fluid vaporization in this deceleration-decrease occurred at point **a** in Fig. 10, because the pedal travel was not measured in this test.

In the 73rd braking test, shown as **b** in Fig. 10, a clear and distinct deceleration-decrease appeared with line pressure decrease. Then at this point **b**, it is considerd that heat fade and vapor lock phenomena occurred almost at the same time. There may have also been no pedal reserve. At the starting point of this braking test 1 the deceleration was 0.7g, and moreover, braking wheels did not stop their revolution.

On the other hand tire braking force may take the maximum value at a slip ratio between ca. 0.1-0.2. Then the braking wheels-slip ratio at the point of deceleration-decrease, as shown as **a** in Fig. 10, may be smaller than the one mentioned above in 0.1-0.2. According to other studies[1] it is difficult to detect faint skidmarks printed during a slip ratio between 0.1-0.2.

It may not be possible to determine that clear skidmarks were printed at the first stage of heat fade and vapor lock as shown as **a** in Fig. 10.

3-2. Braking test (2).

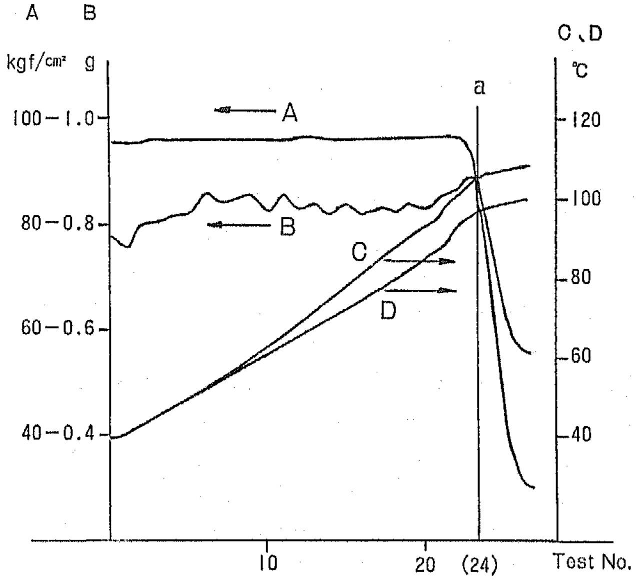

Fig. 11 An example of braking test (2) results.
A : Line pressure.
B : Braking deceleration.
C : Brake fluid temperature (outer piston).
D : Brake fluid temperature (inner piston).

An example of these tests results is shown in Fig. 11. In this Figure **A**, **B** are line pressure and braking deceleration respectively, and **C**, **D** are brake fluid temperature in the right front calliper. In this case, at the 24th braking test, shown as **a** in Fig. 11, line pressure and deceleration-decrease occurred simultaneously. But it is not clear from this test that this deceleration decrease depend on only the heat fade or compolymerization of heat fade and vapor lock. This kind of decrease is very complicated because it changes with types of disk pad and ambient temperature etc..

No wheel locked at the first stage of this emergency braking test 2. So, for reasons similar to those found in the test 1, it may be difficult to detect the faint skidmarks left on the road surface at the first stage of heat fade and vapor lock with the naked eyes.

At a value shown as **a** in Fig. 11, brake fluid temperature is nearly equal to the boiling point of the fluid and the braking deceleration is greatly decreased. At this time, clear vapor lock phenomena occurred. Brake fluid temperature in the cylinder body of the outer piston is always higher than in the inner one, as shown in Fig. 11. This is because the air cooled brake fluid in tube, connected to the cylinder for the inner piston, is compressed into the calliper.

3-3. High temperature test.

An example of the former test results is shown in Fig. 12. In this Figure **A**, **B**, **C** are line pressure, brake fluid temperature and master cylinder-push rod travel respectively. At the value shown as **a** in Fig. 12, the fluid temperature rises to 120°C (393°K) to be nearly equal to the boiling point and line pressure decreases and push rod travel increases instantaneously. At the value of **b**, line pressure and push rod reserve are nearly equal to zero. It may be considered that clear vaporization of brake fluid, or vapor lock phenomenon occurred at this point **b**. At a temperature lower than the boiling point, no vapor lock phenomenon occurs. In the tests shown by Fig. 12, when the fluid temperature is 5°C (278°K) lower than the boiling point, braking pedal travel is very short after ca. 20 minutes heating (refer to the point **c** in Fig. 12). So it may be concluded that the heat fade and vapor lock phenomena and the vehicle deceleration-decrease may not easily happen when the brake fluid boiling point is high.

An example of the latter test results is shown in Fig. 13. At a point shown as **a** in this Figure, master cylinder push rod travel begins to increase with the increase of the fluid temperature. But as is evident from Fig. 13

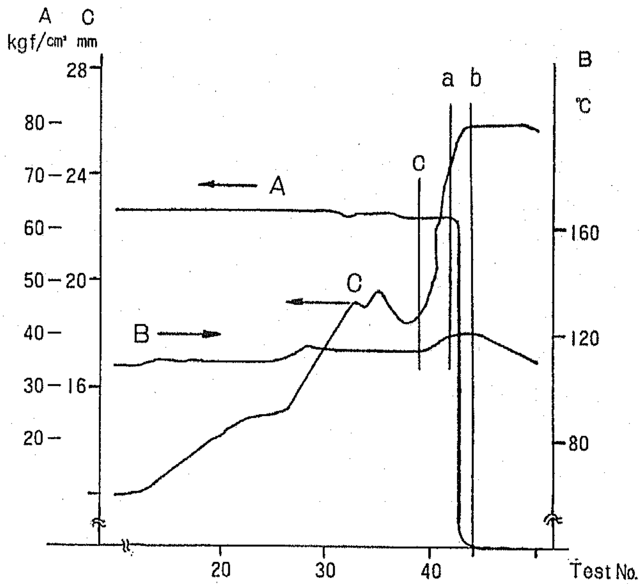

Fig. 12 An example of high temperature test results.
A : Line pressure.
B : Brake fluid temperature.
C : Master cylinder-push rod travel.

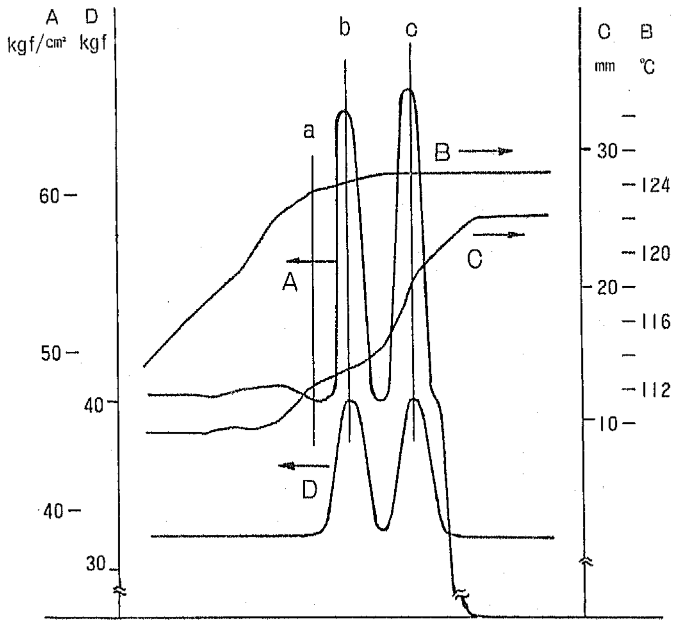

Fig. 13 An example of high temperature test results.
A : Line pressure.
B : Brake fluid temperature.
C : Master cylinder-push rod travel.
D : Pedal effort.

if the fluid temperature does not reach the boiling point, the master cylinder push rod reserve does not become zero. So we can elevate the line pressure by increasing the pedal effort as shown by the value of **b** and **c**.

We can conclude from this "high temperature test", that a slight braking deceleration-decrease, which may occur at the first stage of heat fade and vapor lock phenomena, may be repaired by increasing pedal effort.

3-4. Braking test (3).

One of the test results is shown in Figs. 14, 15 and Table 1. As is evident from Table 1, from the first test to the 11th, braking wheels locked relatively easily, but it became rare after the 12th. At this point it might be presumed that the heat fade and vapor lock phenomena, and decrease of braking force in the braking system began to occur. But at the 14th braking test, incresing the pedal effort from 25 kgf (245 N) to 50 kgf (490 N) made the vehicle wheels lock again during braking. So we can treat the 12th braking test as the first stage of heat fade and vapor lock and it may be presumed that there was some pedal reserve.

On the other hand, there was no major difference between the 13th and

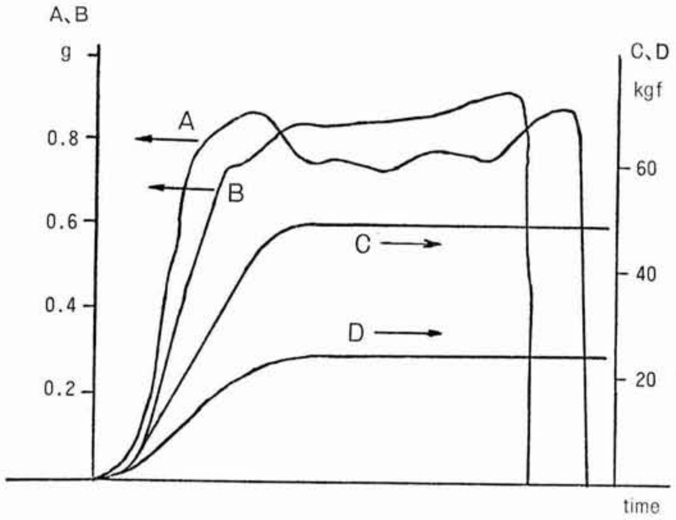

Fig. 14 An example of braking test (3) results.
A : Braking deceleration (No. 14).
B : Braking deceleration (No. 13).
C : Pedal effort (No. 14).
D : Pedal effort (No. 13).
No. 13, 14 in Figs. 14, 15 and Table 1 are correspond to each other.

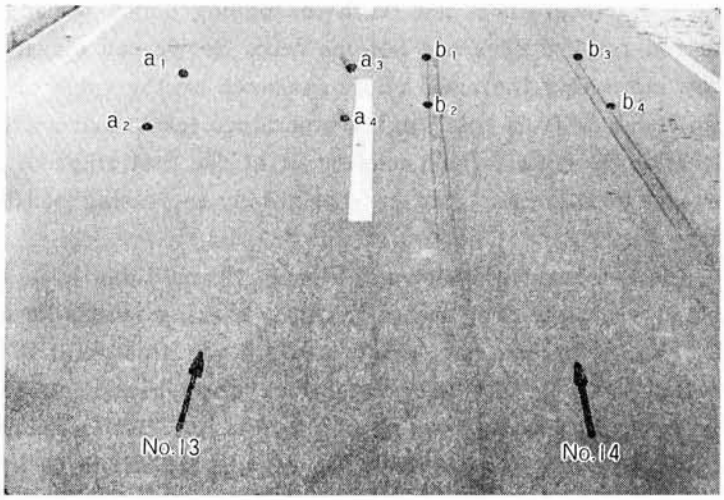

Fig. 15 An example of braking test (3) results.
The points of a_1, -, a_4 and b_1, -, b_4 are braking wheels-stopped ones. The arrow ↑ indicates the test car-running direction.

Table 1 A distinction of braking wheel-lock or-unlock phenomena in braking test (3).

○ : Locked wheel skid distance occupies the major portion of active braking distance.

△ : Locked wheel skid distance occupies the minor portion of active braking distance.

— : Braking wheel doesn't lock during braking.

Experiment	Front wheel		Rear wheel		Pedal effort	Initial speed
No.	Right	Left	Right	Left	kgf	km/h
1	—	—	○	○	25	50
2	—	—	—	—	↑	↑
3	○	○	○	○	↑	↑
4	○	○	—	—	↑	↑
5	○	○	○	○	↑	↑
6	—	○	○	○	↑	30
7	—	○	—	—	↑	50
8	—	△	○	○	↑	↑
9	—	—	—	—	↑	↑
10	—	○	○	○	↑	↑
11	—	—	○	○	↑	↑
12	—	△	—	—	↑	↑
13	—	—	△	—	↑	↑
14	○	○	○	○	50	↑
15	○	○	○	○	↑	30
16	○	○	○	○	↑	50
17	○	○	—	—	↑	30
18	○	○	—	—	↑	50

14th braking decelerations shown on Fig. 14, and the average of braking deceleration in the 13th test is larger than that in the 14th. Four wheels locked easily at the initial stage of this test 3.

Therefore, it is presumed that the slip ratio in the 13th test was between 0.1-0.2 or more. From other research[2)], we know it is possible for 50% of female drivers to generate 30 kgf (294 N) of brake pedal effort. It is also possible for 50% of male drivers to generate 50 kgf (490 N) of brake pedal effort. So it may be that at the first stage of heat fade and vapor lock phenomena, female drivers can print only faint skidmarks, but male drivers can print clear skidmarks in spite of there being no large difference of vehicle braking deceleration between male and female drivers.

On the basis of 3-1, 3-2, 3-3, 3-4 and our field inspections we may discuss the following results.

(1). Heat fade and vapor lock phenomena are independent of each other, but these phenomena are closely related to each other and they may not occur independently. The decrease of braking force and braking deceleration occurred according to these phenomena. It is possible to stop their decrease and also to increase the braking force to some degree by increasing the braking pedal effort, only when there is pedal reserve at the first stage of heat fade and vapor lock. In this case braking wheels are able to lock with black and clear skidmarks on road surface textures.

(2). In general, the braking force-decrease in the braking device occurs at the first stage of heat fade and vapor lock phenomena. This decrease in the stability of the braking device effect may be able to make braking force increase, because the braking wheels-slip ratio decreases from 1.0 (that is the state in which wheels are locked), and may reach to 0.1-0.2 (the state of the maximum value of braking force). So in this case it is more difficult to detect skidmarks on road surface textures by unaided eyes.

(3). It is possible to consider that the phenomena mentioned below (3)-1, (3)-2, (3)-3, which we encounter in the braking tests and in the road accident investigations, occur at the first stage of heat fade and vapor lock phenomena.

(3)-1. In vehicles using brake fluid with a low boiling point, the time interval between the start of brake pedal operation by the driver and braking wheels locking is different according to the initial speed of braking. For example, a difference of 0.6 second occurs in the case of the initial speeds : 30km/h (8.3m/s) and 60km/h (16.7m/s).

(3)-2. A passenger car, having no line pressure control valve for wheel lock prevention, and driven by a female can not make clear skidmarks on micro coarse textures whose textures are one of the most printable of skidmarks.

(3)-3. In a high ambient temperature, vehicle braking wheels rarely lock during braking with ordinary pedal effort.

4. CONCLUSIONS.

In order to learn the relationship between skidmarks and the stability of braking device effect, especially the relation between skidmarks and the first stage of heat fade and vapor lock phenomena, passenger car-emergency braking tests and braking fluid-high temperature tests were carried out.

The following results were obtained.

4-1. In the first stage of heat fade and vapor lock phenomena, one of the instable phenomena of braking device effect, there occurs braking force-decrease in braking device, decrease of braking wheels-slip ratio and vehicle braking deceleration-increase caused by the ones mentioned above, leaving faint skidmarks.

4-2. In the first stage of heat fade and vapor lock phenomena, when there is a brake pedal-reserve, it may be possible to operate the braking device with slip ratio of 1.0 by increasing pedal force, leaving clear and black skidmarks.

4-3. In the first stage of heat fade and vapor lock phenomena, only faint skidmarks may be left with large vehicle deceleration, even if the road surface textures are micro coarse ones, the braking device has no line pressure-control valve for wheel lock prevention and moreover free running time by the driver is very short.

5. ACKNOWLEDGEMENTS.

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6. REFERENCES.

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