A CONSIDERATION OF TIRE-ROAD TRACTION MEASURING METHOD IN JAPAN

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As in many other countries, many traction measuring methods have been used in Japan. For example, there are such methods as measuring stopping distance, deceleration of a car when braking force is applied, braking force or torque obtained by a instrumented towed trailer or a vehicle with wheel etc. for measuring braking traction. For measuring cornering traction, we have maximum speed at which a tethered or non-tethered car being driven in a circle at increasing speed loses control, the relation between cornering or lateral force and slip angle obtained by a towed trailer or a vehicle with a fifth wheel etc. Several indoor testing methods are also used. Since tire-road traction mechanisms of cars driven on public roads are very complicated, one must consider the purpose in measuring such traction. One case may be to evaluate whether the tires are suitable for the market. Another may be to research tire traction problem. It is difficult to measure all the characteristics of tire traction with any one measuring method and a suitable method or methods for the purpose should be selected. In addition, the subjective feeling of the driver should be considered as to the ease of driving control, because cars are driven by human beings. This paper introduces tire-road traction measuring methods used in Japan and discusses their advantages and disadvantages from the previously mentioned standpoints. It also reports on a newly developed tire traction testing vehicle along with several typical test results.

As the road traffic network has been enlarged, slip accidents on roads have been regarded as important in Japan. Accordingly, tire-road traction measurements have increasingly been made in various fields and many papers have been published. This paper describes, based mainly on the published papers, tire-road traction measuring methods used in Japan with an introduction of these activities, and a discussion of their advantages and disadvantages. Finally, it reports on our developed tire traction testing vehicle along with its typical test results.

Tire-Road Traction Measurements in Japan

Measurements on Highways

In 1959, the Automobile Research Committee of the Highway Investigation Association conducted various tests on newly built highways prior to their opening (1). They aimed to investigate technical problems on highway including tire-road traction. The committee consists of the Public Works Research Institute of the Ministry of Construction, Japan Highways Public Corporation, the automobile industry, the tire industry, the oil industry, the universities etc.

For the tire-road traction, both braking traction and cornering traction were measured. Stopping distances were measured for braking traction. Cornering traction measurements were made using a two wheel type towed trailer developed by the Public Works Research Institute of the Ministry of Construction. Slip angles were applied to these wheels discretely by toe-in setting so that cornering force and cornering drag were measured at each slip angle. The vector summations of cornering force and cornering drag were made to obtain the side force.

In 1961, when a part of Meishin Expressway was built, the committee repeated almost the same tests (2). For braking traction, the stopping distance method was used again. For cornering traction, however, this time a bus which had a cornering force measuring device was used. The device had two test wheels under the bus floor and their slip angles were set in the same way as with the above mentioned towed trailer.

Activities of the Ministry of Construction

The Public Works Research Institute of the Ministry of construction published a report in 1966 and the revised one in 1967 (3, 4). According to these reports, they built a bus type heavy testing vehicle. The testing vehicle had two devices installed. One of them is a device to measure locked wheel skid-resistance and to measure the side force achieved by slip angle setting. Another is a device to measure skid-resistance vs. slip ratio. This is a sophisticated device. Two wheels are connected by a transmission gear and one wheel is loaded more heavily than the other on which a test tire is mounted. The heavily loaded wheel rotates at the same speed as the vehicle, on the other hand the test wheel is rotated with slip depending on the gear ratio.

Using the testing vehicle, they measured many roads in Japan to investigate the change of the coefficients with the passing of time. The data appearing in these reports are mainly the longitudinal coefficients of friction obtained by locked wheel values. There are also a few lateral coefficients of friction at 10 degrees and 20 degrees of slip angle.

There are two other testing vehicles in the Institute (5). One is a bus with a fifth wheel to which braking force is applied to the point of lock to measure the locked wheel skid-resistance. This vehicle carries a water tank for spraying.

Another is a high speed testing vehicle with a fifth wheel which can be locked and can be set with slip angle. The test wheel is installed in front of the vehicle to prevent any influence of water splashed by the front wheels. Using this vehicle, they have also measured various roads in Japan. Additionally, they made hydroplaning tests (6). The vehicle ran on a test road heavily water covered and the locked wheel skid-resistance was measured.

Each regional office of the Ministry of Construction possesses the standard skid testing vehicle to measure roads under its control for maintenance. This testing vehicle is a simple one with a fifth wheel to measure the locked wheel skid-resistance (5).

Comparative Test of Traction Testers

In 1971, the Stability and Control Research Committee of the Japan Automobile Research Institute conducted a test program to make comparison of the tire-road traction testers in Japan (5, 7). Participants in this program were three testing vehicles from the Public Works Research Institute, five from the regional offices of the Ministry of Construction, two from the Japan Highways Public Corporation, three towed trailers from the automobile industry, four from the tire industry and one from JARI. The testing vehicles from the Ministry of Construction were those mentioned before.

One of the testing vehicles from the Japan Highways Public Corporation had a fifth wheel which could measure the locked wheel skid-resistance. Another could measure both the longitudinal traction and cornering traction.

All three towed trailers from the automobile industry were, in principle, the same as the ASTM's two-wheel trailer and locked wheel torques could be measured.

Three towed trailers from the tire industry were also two-wheel trailers with which, in addition to measuring the locked wheel skid-resistance, side force could be measured. Slip angles were applied by toe-in settings. The other one was a one-wheel trailer. A two-axis load cell was installed on the test wheel axis so that dynamic load and locked wheel skid-resistance were measured. The towed trailer from JARI was almost the same as three trailers from the tire industry.

In this cooperative program, the longitudinal coefficients of friction of locked wheel and the lateral coefficients of friction at fifteen degrees of slip angle were obtained and compared. The test results are described later in this report.

Cooperative Programs in the Tire Industry

The Testing Committee of the Japan Automobile Tire Manufacturers Association conducted a program to study the relation between wet skid-resistance and tread wear from 1967 through 1970 (8, 9). In this program, both passenger car tires and heavy duty tires were tested. For longitudinal traction, stopping distances were measured and for cornering traction, the maximum speeds and lateral accelerations at which non-tethered cars being driven in circles at increasing speeds lost control were measured. For passenger car tires, the heavy testing vehicle of the Public Works Research Institute was also used.

From 1974 through 1975, the Testing Committee had studied the difference of traction property between rib tread and lug tread of heavy duty tires (10). At that time, in addition to the stopping distance and non-tethered cornering two other tests were run. In one, a test truck was driven with full acceleration from a starting point to fifty meters away and time taken for this distance was measured. In the second, a truck with test tires on rear wheels pulled a heavy truck with brakes applied on a wet road. This is a static test and the heavy truck is used as an immovable object. Peak drawbar was measured.

Coefficient of Friction vs. Slip Ratio

To the best of my knowledge from published papers, there are, in Japan, five test vehicles which can measure longitudinal traction at any slip ratio. One of them is the testing vehicle of the Public Works Research Institute which has two test wheels connected by a transmission gear, as described before. Each of three others has an extra engine by which test wheels are forcibly rotated at any given speed (11, 12, 13, 14). The difference between the testing vehicle speed and the test wheel speed creates a slip between the test tire and road surface.

The last one is a sophisticated towed trailer without any extra engine rotating the test wheels (15). This has a fly wheel with large moment of inertia and a electronic control system to prevent lock-up after a peak of friction has been reached.

Other Cornering Traction Measuring Methods

In addition to those mentioned above for cornering traction, there is another test vehicle developed by the author's team (12, 13). It will be described in detail later. A tethered cornering test method was also used (16).

There are no publications, but the automobile industry and the tire industry have seen many subjective tests on wet roads such as slalom, lane change and J-turn to evaluate cornering traction performances.

Hydroplaning

A test method of hydroplaning was such that a one wheel towed trailer ran in a water filled shallow ditch and the speed at which the test wheel spun down was measured (17). A transparent glass plate was set on a bottom of the ditch under which was an underground room and photographs of tire-glass contact patch could be taken through the glass plate from the room.

The high speed testing vehicle of the Public Works Research Institute was used to test hydroplaning as mentioned before.

Indoor Testing Device

I have once tried the test of wet skid-resistance on the outside of a steel drum, but there was a difficulty with controlling the water depth. JARI has an inside surface drum tester. A test tire is loaded to inside surface covered by water. The longitudinal traction and cornering traction are measured. Using this device, the hydroplaning problem has been studied (18, 19). The water depth can be easily controlled on the inside surface. They are using needle type probes to measure the water depth.

The so-called British Portable Tester has also been used as a convenient method to evaluate road surfaces mainly in the road construction industry and research institutes.

Summarization of the Testing Methods in Japan

The summarization of the wet traction measuring methods used in Japan is as follows:

Road Construction Administration, Industry and Research.

1. Skid number by British Portable Tester.
2. Locked wheel skid-resistance by the testing vehicle with the fifth wheel.
3. Coefficient of friction vs. slip ratio by the testing vehicle with the fifth wheel.
4. Cornering force vs. slip angle by the testing vehicle with the fifth wheel.

Automobile Industry, Tire Industry and Research.

1. Stopping distance and deceleration by car.
2. Locked wheel skid-resistance by the testing vehicle with the fifth wheel or the towed trailer.
3. Coefficient of friction vs. slip ratio by the testing vehicle with the fifth wheel or the towed trailer.
4. Start and dash test.
5. Drawbar test.
6. Non-tethered or tethered cornering.
7. Cornering force vs. slip angle by the testing vehicle with the fifth wheel or the towed trailer.
8. Subjective feeling test.
9. Indoor test.

Discussion on Advantages and Disadvantages of Each Measuring Method

I have been working for the tire industry, the discussion, therefore, is mainly made from a standpoint of a tire engineer.

Several Test Results

On Temperature. Wet traction is too much affected by various factors to obtain its test results without variations. An asphalt paved test course of JARI which we have often used is 1,000 m. long, 45 m. wide in a half length and 30 m. in another half. Skid numbers by the British Portable Tester on the test road surface were measured from December in 1969 to November in 1970 (20). Figure 1 shows the test result. Each number on the abscissa shows month, that is, "1" is "January", "2" as "February", "3", "March" and so on. "BSN" means the "British Skid Number". Each dot shows the average of each month. From this Figure 1, one can see that BSN depends on temperature.

An empirical formula of BSN vs. temperature derived from all the measured values (N=439) is as follows;

$$BSN = - 0.32T + 69.75 \text{ (Asphalt)}$$

where "T" is temperature in degrees of centigrade and coefficient of correlation "r" is 0.85.

Figure 1. BSN on asphalt through a year.

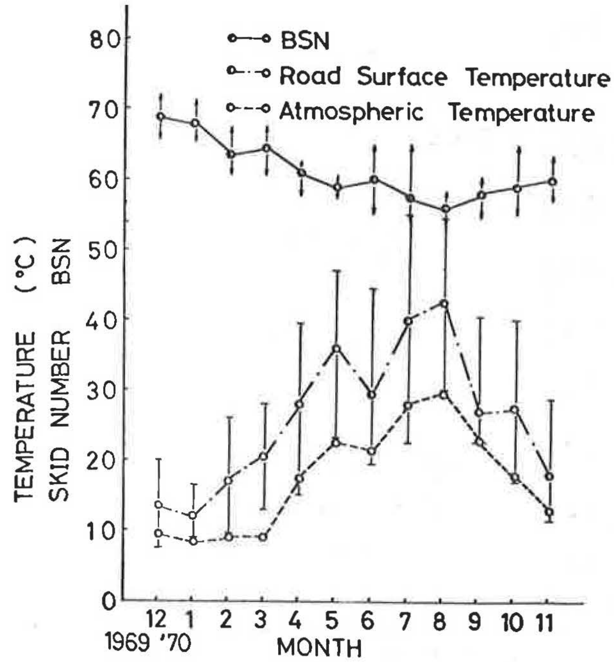
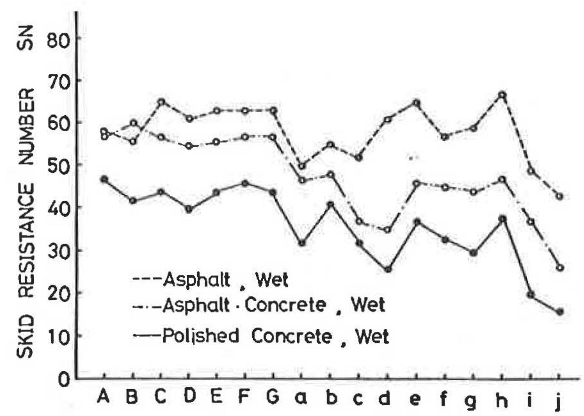


Figure 2. Longitudinal skid-resistance number.



A distribution study of BSN on the asphalt test course was also made and the result showed that the average of the 405 points measured was 66.0 with 2.3, the standard deviation.

The same measurements as on the asphalt were made on other test course surfaces. The empirical formulae of temperature dependency on concrete and polished concrete are as follows:

$$BSN = - 0.31T + 73.33 \text{ (Concrete)}$$

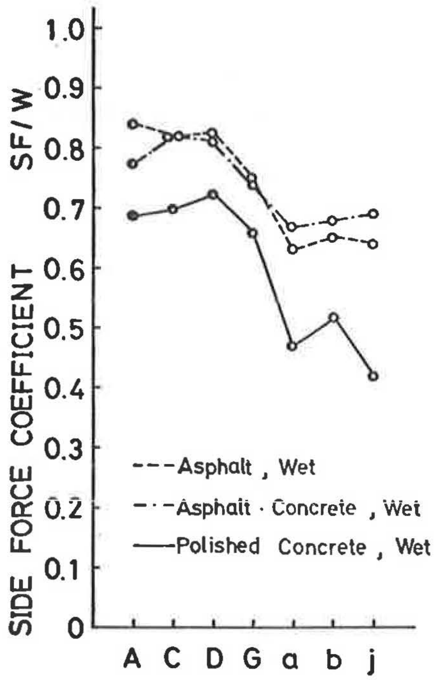
where N = 187, r = 0.59.

$$BSN = - 0.31T + 72.17 \text{ (Polished Concrete)}$$

where N=319, r=0.75. In this case, the measurement was made from July to November in 1970 and from January to September in 1971.

These data include influences of such factors as road surface texture, water thickness, temperature etc. If one goes much into details to examine the data, he might be confused with their variation, however, if he tries to find some general tendency per-

Figure 3. Side force coefficient.



mitting some variations, he might derive, in this case, the temperature dependency of BSN.

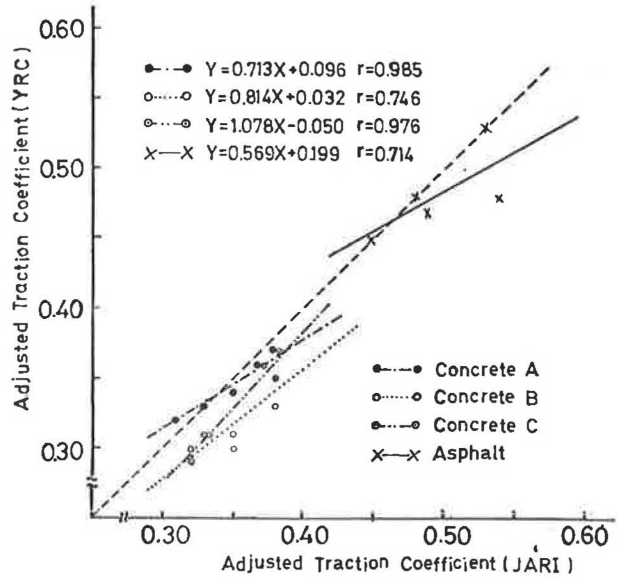
On Traction Testers. As described before, a comparative test of traction testers was made. Figure 2 shows the longitudinal skid-resistance numbers on three different road surfaces obtained by participant testers. A, B, C, D, E, F and G on the abscissa show towed trailers from the automobile industry and the tire industry. While a, b, c, d, e, f, g, h, i and j are the testing vehicles with the fifth wheel from the Ministry of Construction and the Japan Highways Public Corporation.

Test tires for the towed trailers were 7.50-14-4PR ASTM standard tires. For the testing vehicles, those were 5.60-13-4PR rib patterned tires secured from the market. The skid-resistance number is the ratio of the skid-resistance force to the tire load in percentage.

There are fairly big variations with SN even between the same type testers. Regarding the tester "B", the SN on asphalt is smaller than the value on asphalt-concrete, despite the fact that the data by other testers show vice versa. SN on polished concrete by the tester "b" is higher than SNs on asphalt-concrete by the testers "c", "d", "i" and "j". Comparing the tester type, one can see that the average of the SNs by the towed trailers on each surface is higher than the average by the testing vehicles. Accordingly, one might be in difficulties in comparing SNs on different surfaces by different testers. Noticing, however, SNs on different surfaces by the same tester, except "B", one can recognize that the highest is the asphalt, middle the asphalt-concrete and the lowest the polished concrete.

Figure 3 shows the side force coefficient. Test tires used were the same as for the longitudinal traction measurements. The side force coefficient is the ratio of the side force at 15 degrees of slip angle to the tire load. Symbols on the abscissa are the same as those in Figure 2. We have a further problem. It is that, though differences are small, the side force coefficients on asphalt by towed trailers are

Figure 4. Comparison of ASTM type towed trailers.



higher than those on asphalt-concrete, while the values on asphalt by the testing vehicles are smaller than those on asphalt-concrete.

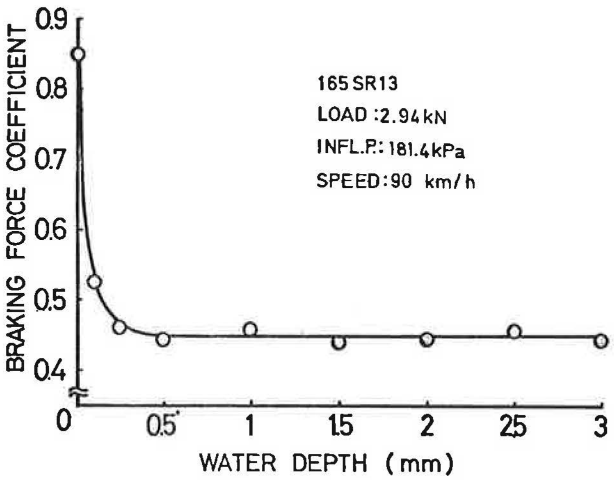
Recently, the Tire Testing Course Subcommittee of the Japan Automobile Tire Manufacturers Association has conducted a cooperative program to construct a tire wet traction testing course. The Subcommittee consists of the members from the tire industry, JARI and the road construction industry. Many basic studies have been made, but no report has been published as yet. Figure 4 shows a result of the studies. In this study, three towed trailers made test runs on three kinds of concrete surface and an asphalt surface. All the towed trailers used were the two wheel type, completely following the ASTM specification. Test tires used had five different patterns which were selected so that the coefficient of frictions might be in wide range. ASTM standard tires were also used to obtain the Adjusted Traction Coefficients following the method in the Uniform Tire Quality Grading Standard issued by NHTSA in U.S.A.

The test results shown in Figure 4 are the correlations of the coefficients between the JARI's and the Yokohama Rubber Company's (YRC). From this figure, one can see that the coefficients obtained by JARI's trailer are not always the same as those by YRC's. If the data can be seen, with allowance for some variation, it is considered that there is a good correlation between them on the whole.

On Water Depth. Road surfaces are usually uneven in both macroscopic and microscopic aspect even on a test course so that the water depth at each spot changes. As the wet skid-resistance is influenced by the water depth, it changes at every spot on the road surface during the measurement. Therefore, one has no choice but to obtain an average of several measurements to evaluate the tire wet traction performance.

Despite wet traction is influenced by the water depth, the test should be made under such conditions as those mentioned above. I once conducted a study to investigate to what extent the wet traction is influenced by the water depth under these practical conditions. The test was made on the JARI test course. The water depth ranged from zero to three millimeters, because the water depth on well paved

Figure 5. Influence of Water depth on braking force efficient.



road surfaces on ordinary rainy days seems to be three millimeters or below. The tires tested were new tires which had sufficient skid depth.

There was no water spraying device on the test course, so a watering cart was used. The water depth was measured by a NASA Water Film Depth Gage. Figure 5 shows the test result. The braking force coefficient was obtained by the locked wheel skid-resistance. Since the water began to flow immediately after being sprayed, the depth changed every moment so that there was a large variation in the water depth measurement. Water depth on the abscissa in Figure 5 should be, therefore, considered as the nominal value. Contrary to my expectation, the coefficient scarcely depended on the water depth in the range from 0.5 to 3 millimeters.

Discussion on Each Measuring Method

Each measuring method has its own special feature. This feature may have advantages for measuring wet traction in some cases and have disadvantages in others. Therefore, each will be briefly discussed in this section.

Stopping Distance. The stopping distance method is the easiest one of the outdoor tire-road wet traction measuring methods. It only requires a car without any instrumentation, several stop-watches, a measuring tape and several technicians including a driver.

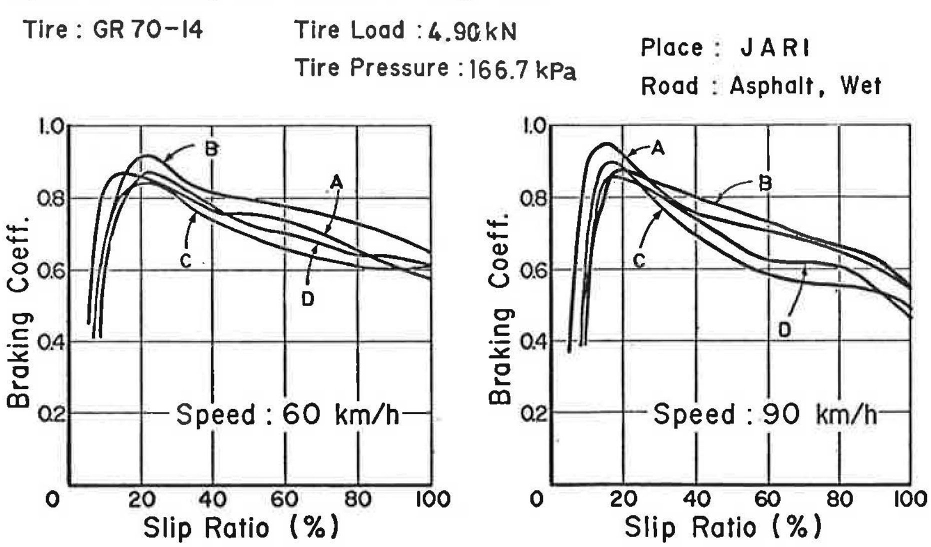
This test method is the closest to a practical operation of a car on a public road, especially in the case of emergency. It includes the car performance, the test tire performance and the driver characteristics. Accordingly, the obtained values show the most practical meanings and are understandable for everyone. These are advantages. Since the test method is, however, a transient test method in which many factors affecting the tire-road wet traction such as the speed and the force of the braking operation, the moment of inertia of rotating parts of the test car, slip ratio between the tire and the road surface, deceleration of the car, air resistance of the car etc. are included, it is difficult to analyze the tire performance itself. This is a disadvantage. The available maximum speed depends on the driver's skill. From my experience, the maximum safe speed is about 100 km/h.

Locked Wheel Skid-Resistance. This testing method needs instrumented testing devices. As described before, there are the towed trailers and the testing vehicles with the fifth wheel.

This is a steady state testing method in which the locked wheel skid-resistance can literally be measured. It is, therefore, easy to analyze the tire performance, but it includes only the locked wheel skidding process and does not include the other brake applying processes. This is a disadvantage for the tire engineers. Since the coefficient of friction of the locked wheel on wet road is usually lower than the peak value, this gives a good information with some safety margin for the road construction engineers and researchers. The so-called jackknife phenomenon tends to arise with the towed trailer at the high speed.

Coefficient of Friction vs. Slip Ratio. For the tire engineers, it is very valuable to obtain the peak coefficient of friction and, if possible, the relation between the coefficient of friction and the slip ratio in steady state.

Figure 6. Braking coefficient vs. slip ratio.



The data show us the peak value, the locked wheel value and the values at the other slip ratios, all in steady state.

We built a tire traction testing vehicle to obtain this relationship. A description of the testing vehicle will be made later.

Figure 6 shows a test result obtained by the testing vehicle. Tires from the market were tested all with different patterns. The figure 6 shows many things which arise between the tires and wet road surfaces. It is outside of the purpose of this paper to discuss the test result in detail, but one thing is discussed as an example. The peak values of "A" and "C" increase, the "B"'s decreases and the "D"'s is almost the same as the speed increases, while the locked wheel values all decrease. The slip ratios of "B", "C" and "D" at which they have the peak values tend to decrease with the speed increasing. The slip ratio of "A" is, however, almost the same. Since we usually operate the brake within the braking coefficient ranging from zero to the peak value in normal driving, we should know the peak value to evaluate the tire traction performance. Analyzing these facts, we can also study influence of tread pattern and of hysteresis loss of tread compound on the tire wet traction.

The testing vehicle with which the coefficient of friction at any slip ratio can be obtained needs an extra engine to rotate the test tire at any speed independently of the testing vehicle speed. In case of the towed trailer, the trailer with the extra engine tends to be heavy so that the maximum test speed is limited to maintain stable running. We are now using a big high speed bus.

Start and Dash Test, and Drawbar Test. These are the test methods whose test results depend on the test driver's skill. These are not suitable for tire engineers.

Non-Tethered Cornering. This is the simplest method to test the tire's wet cornering traction. The test result includes the car performance, the tire performance and the driver's characteristics. The driver can easily understand the maximum speed with which he can turn a corner from the test result. However, it includes too much information to analyze the tire wet cornering performance.

Cornering Force et al. vs. Slip Angle. To study the tire wet cornering traction, it is desirable to obtain the relation between the cornering force or self-aligning torque and the slip angle. Our testing vehicle can also measure the cornering force and self-aligning torque at any slip angle. This will be introduced later.

When a car turns a corner, a load transfer occurs and a camber angle is set to the tire. The camber angle causes a camber thrust. The camber thrust of the radial tire is very small, but the shape of the tire-road contact patch is at least changed so that the distribution of the contact pressure is changed. It is desirable that a testing vehicle with which these conditions can be simulated be established. The mechanisms are, however, so complicated that it is difficult to establish such a testing vehicle to obtain accurate data. For this, the non-tethered or tethered cornering method gains an advantage.

To evaluate road surfaces, the measurement of the cornering force at any fixed slip angle between ten and fifteen degrees may be satisfactory.

Subjective Cornering Test. Since a car is driven by a human being, a feeling test by the driver is also important. The tire industry and the automobile industry often run this test.

In the objective test, the physical measurements, that is, the pulse response, are also made to obtain the ability of a car response including tire performance. It takes a great deal of time from running the test to obtaining test result; also the accuracy is not so high. The subjective test is made more often than the objective test.

Indoor Test. The most important advantage claimed for the indoor test is that each testing condition can almost completely be controlled. The water depth on an outisde surface of a roadwheel can not be well controlled, but when using the inside surface, it may easily be controlled. However, there may be problems in the curvature, the texture and the material of the roadwheel surface. I do not have personal knowledge of the indoor testing machine using the inside surface of the roadwheel, and I can not discuss this item further.

General Discussion on Measuring Method

As mentioned above, the tire-road wet traction is influenced by many factors. To obtain valuable data, it is important that the variations of these factors should be minimized as much as possible.

The tire wet traction has usually been measured with a fixed measuring device and on a fixed road surface in comparison test with a reference tire. Road construction engineers have measured the road wet traction property with a fixed device and a tire. To minimize the variation of the test result, the measurement should be repeated several times and the average should be obtained.

There are many measuring methods and each method

Figure 7. Driving and braking traction testing device.

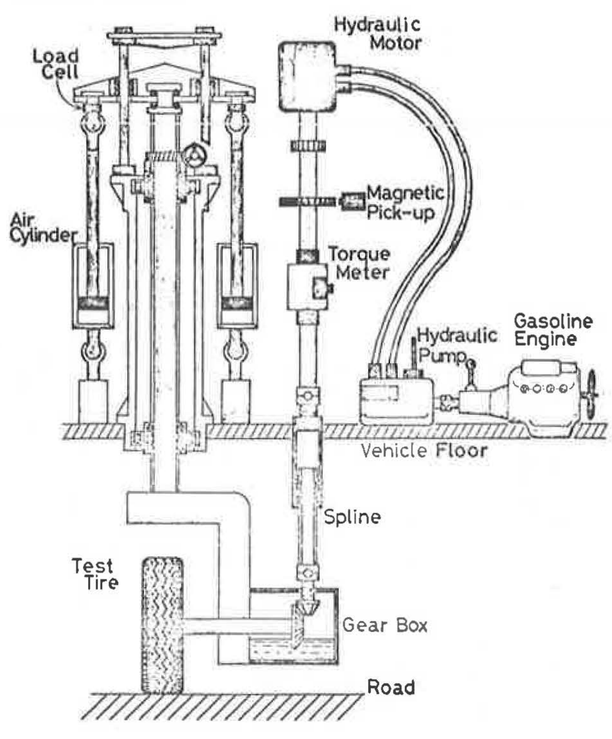


Figure 8. Instrument diagram for driving and braking traction testing device.

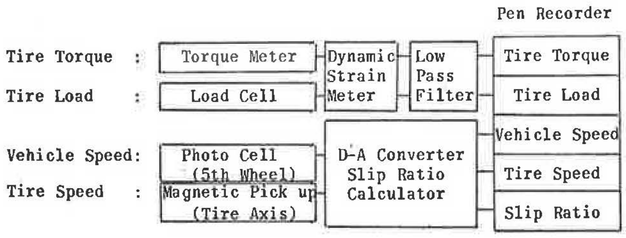


Figure 9. Cornering traction testing device.

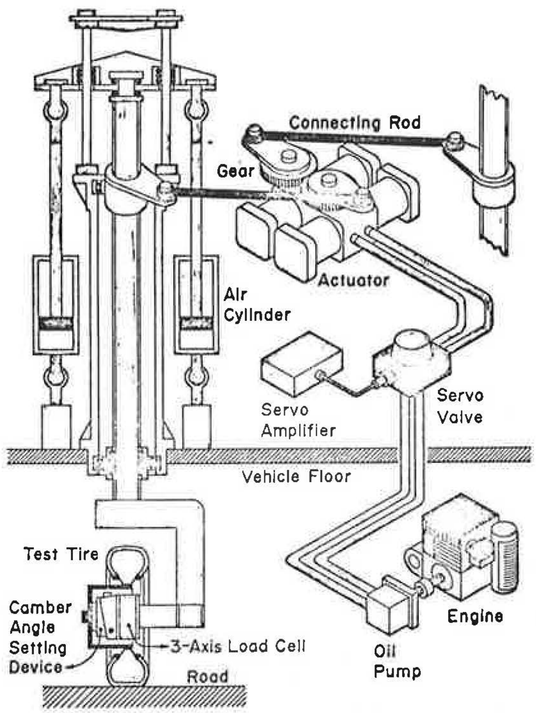
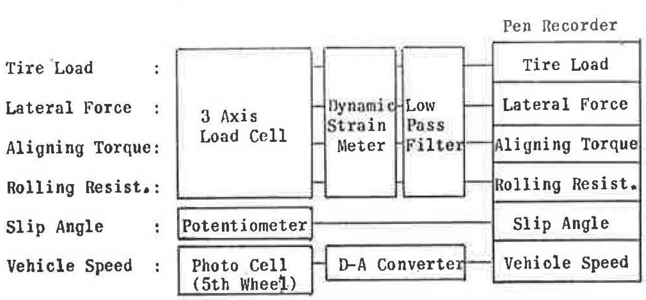


Figure 10. Instrument diagram for cornering traction testing device.



has advantages and disadvantages. One should select the method suitable for his purpose.

Tire Traction Testing Vehicle by the Yokohama Rubber Company

It is valuable for tire engineers to obtain the relation between the tire longitudinal friction and the slip ratio, and between the cornering force or

Figure 11. Lateral force vs. slip angle.

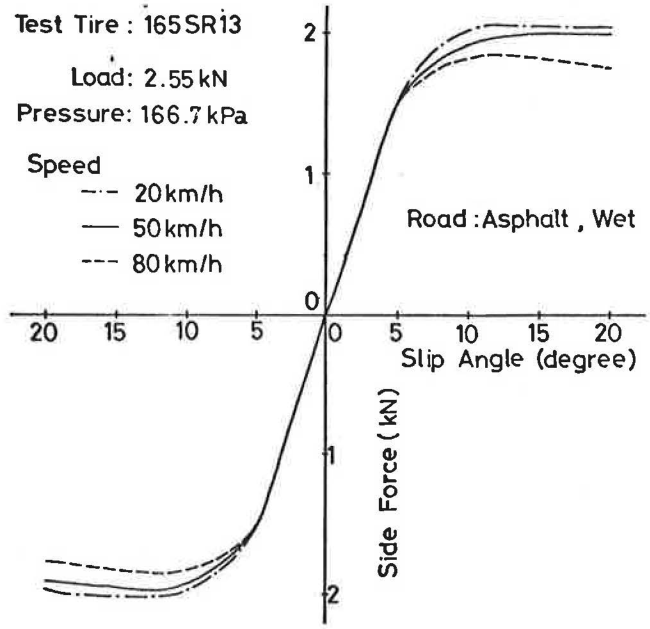
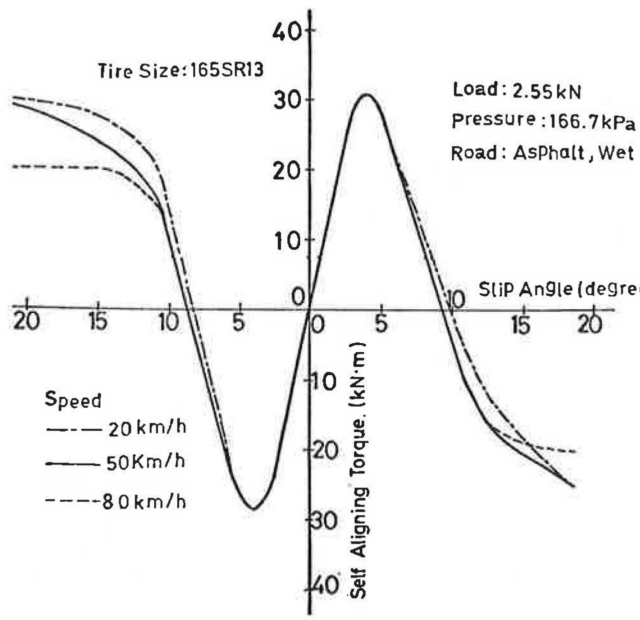


Figure 12. Self-aligning torque vs. slip angle.



self-aligning torque and the slip angle on the wet road surface. We scheduled to establish this kind of testing vehicle as completely as possible.

There were several problems, especially regarding the tire cornering traction. As described before, it is desirable that, in addition to the steady state, the cornering traction of the braking or driving tire can be measured. It is also desirable that the cornering traction can be measured under a transient condition caused by load transfer, that is, the combination of dynamic slip angle and camber angle. We studied these points and reached an answer that it was too difficult to materialize a testing vehicle which satisfied all these measurements. We, therefore, built a testing vehicle with which the relation between the longitudinal coefficient and the slip ratio, and between the cornering force or self-aligning torque and the slip angle of a free rolling tire could be obtained.

The testing vehicle essentially consists of two devices mounted in a high speed bus, that is, a driving and braking traction testing device and a cornering traction testing device, both for passenger car tires.

Driving and Braking Traction Testing Device

Figure 7 shows the driving and braking traction testing device. A test tire is forcibly rotated at any constant speed ranging from 0 to 100 km/h. by a hydraulic-motor which is driven by a hydraulic pump connected with a big gasoline engine so that any desired constant slip ratio can be achieved. The tire is loaded by two air cylinders.

Tire torque is recorded at each test condition from which tractive force is calculated. Simultaneously, tire load, tire speed and vehicle speed are recorded. Figure 8 shows the instrument diagram for driving and braking traction testing device.

The test devices can accommodate a tire diameter range from 500 mm. to 800 mm., rim size, 12 to 15 inches, tire load 0 to 10,000 N, and vehicle speed which is picked up by a fifth wheel, 0 to 100 km/h. Slip ratio is calculated by tire speed and vehicle speed. Using this system, the relationship between longitudinal coefficient of friction and slip ratio can be obtained under steady state conditions ranging from free rolling to locked wheel. An example of the test result was shown in Figure 6.

Cornering Traction Testing Device

Figure 9 shows the cornering traction testing device. This device consists of two tire carriages such that the lateral forces generated by each test tire cancel out so as not to disturb the vehicle heading direction while testing. Slip angle is set by an electro-hydro-servo system which has a range from 0 to 90 degrees. Tire load, lateral force, self-aligning torque and rolling resistance are all picked up by a sophisticated three-axis load cell. The vehicle speed is picked up by a fifth wheel. All of these measurements are recorded simultaneously. Camber angle is set manually ranging from 0 to 10 degrees. Figure 10 shows the instrument diagram for cornering traction testing vehicle. The measurable range of tire load is 0 to 10,000 N, lateral force, 0 to 10,000 N, aligning torque, 0 to 400 N-m, and rolling resistance, 0 to 10,000 N. Lateral force coefficient is defined as the lateral force devided by vertical tire load. Using this system, one can obtain the relationship between lateral force coefficient and slip angle, between self-aligning torque and slip angle, and between rolling resistance and slip angle.

Figure 11 and 12 show typical examples of lateral force and self aligning torque respectively.

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Note: (J) or (E) at the end of each reference shows that the reference paper is written in Japanese or in English respectively.