Analysis of Instability Factor for Fuel Economy Test on 4WD Chassis Dynamometer

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The four-wheeled drive (4WD) chassis dynamometer has been continually improved by the evolution of power electronics technology and by the inherent design of the chassis dynamometer itself. The need for testing using the 4WD Chassis dynamometer is increasing due to the demand of fuel consumption and emission measurement of vehicles with complex powertrains such as HEVs (Hybrid Electric Vehicles) and PEVs (Pure Electric Vehicles). However, in many cases, the actual performance of 4WD chassis dynamometers has still not actually been confirmed. Accordingly, studies aimed at improvements of the repeatability of 4WD fuel consumption tests have been conducted and some key factors for improving stability and repeatability have been confirmed. It will be shown that most of the vehicle mechanical loss variability is due to the tires and therefore the stabilization of the mechanical losses of the test vehicle is essential for the test reproducibility.

Introduction

The reduction of fuel consumption in automobiles is demanded as a measure against global warming while the number of four-wheel drive vehicles continues to increase in the market as drivers look to their inherent safety and drive quality. Fuel consumption tests on 4WD vehicles have therefore increased in number and importance. However, fuel consumption tests of 4WD vehicles are still being conducted on 2WD chassis dynamometers with their drivelines modified to 2WD. Such tests of vehicles with the 2WD modification cannot determine the real fuel consumption of the vehicle in its 4WD configuration. Additionally, many of the new HEV and EV vehicles cannot be actually tested without a 4WD chassis dynamometer due to their having power transmission / kinetic energy recovery on more than one axle. At the same time, the ability of 4WD chassis dynamometers to simulate the real road load of such vehicles has been improved due the developments in power and control electronics as well as in their detailed design[1, 2]. In reality, there were many issues to be solved before vehicle fuel consumption could be accurately and repeatably determined using 4WD chassis dynamometers. This article summarizes the issues on the parameters that can affect the accuracy and repeatability of fuel consumption measurements on these chassis dynamometers that have been observed over several years of testing such vehicles.

Test Method and Analysis of Results

Test method

The chassis dynamometer load was set to match the resistance experienced, and measured, by the actual vehicle on the road. The fuel consumption was then measured when driving the JAPAN 10-15 cycle. The work at the vehicle wheels was also measured with a six-component wheel force meter at the same time to determine the relationship between wheel work and fuel consumption.

Test vehicles and facilities

The test vehicle chosen was an active-control type 4WD using a four-speed AT (automatic transmission) with a 1.8L normally aspirated engine. The specification of the electric 4WD chassis dynamometer used for the testing is shown in Table 1.

Measurement method

In this project, the work carried out by the vehicle, its fuel consumption, temperature and associated parameters were measured. A six-component wheel force meter as

Table 1 Chassis dynamometer specification

Dynamometer Type	Center motor type 4WD
Roller surface treatment	Chrome
Roller diameter	1219.2 mm
Roller outside edge	2750 mm
Base Inertia	1700 kg + 1700 kg
Electric inertia control range	-3000 - +2900 kg
Vehicle mass simulation range	454 - 6350 kg

shown in Figure 1 was attached to the vehicle to also measure the dynamometer roller surface traction force. The six-component wheel force meter can measure the 3 forces in 3 orthogonal axes applied on the axle and the 6 components of the 3 moments around each axis while the vehicle is actually being driven; while also providing real-time interference and angle corrections. It can also be used to calculate the vehicle speed based on the axle rotation.

The power was calculated every 10 milliseconds, based on the moment of torque as measured by six-component wheel force meter and the wheel rotational speed; this was then integrated for the entire test cycle to provide the quantity of wheel work. The fuel consumption was calculated by integrating the fuel injection command pulse time period and applying the known calibration value. An infra-red radiation type thermometer was also used at the same time to measure the tire surface temperature with a method shown in Figure 2.

Results of fuel consumption measurement

To determine the relationship between wheel work and fuel consumption, measurements were taken under two dynamometer setting conditions :

- Target running resistance (RL1) as measured on the road
- Target running resistance (RL2) with a 20% reduction of only the constant term corresponding to the rolling resistance.

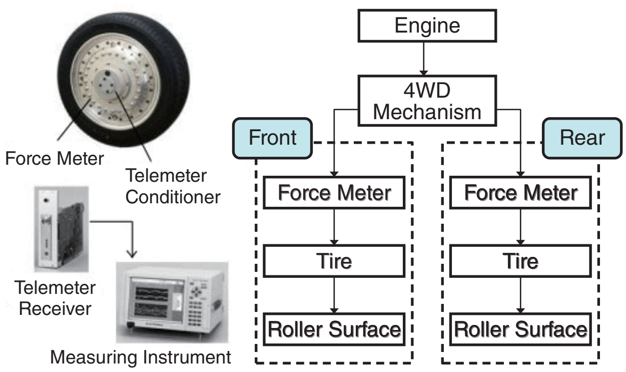

Figure 1 Six-component wheel force meter

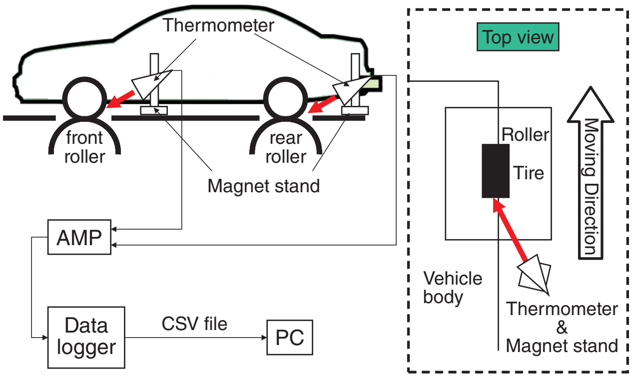

Figure 2 Tyre temp. measurement method

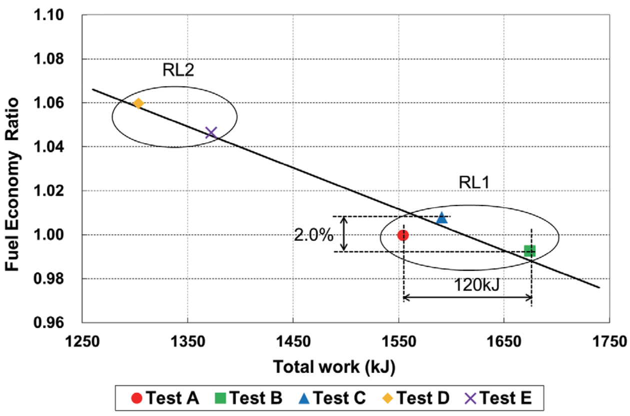

Figure 3 Relationship of Wheel Work and Fuel consumption

Figure 3 shows the relationship between wheel work and fuel consumption in the chassis dynamometer tests[3, 4]. The fuel consumption was calculated as the ratio against the average value of 3 RL1 measurements. There is an overall primary correlation between wheel work and fuel consumption. However, there were differences between Test A, Test B and Test C of RL1 which were using the same target running resistance as well as in wheel work of Test D and Test E of RL2. There was also fuel consumption difference of approximately 2% between Test A and Test C of the same group. Consequently, it was assumed that some factor(s) in test method, facility or other area were causing this difference.

Analysis of the cause of the fluctuation

The possible causes of difference in the wheel work for the same running resistance setting were :

(1) variation of running resistance control by chassis dynamometer

(2) variation of the test method or running resistance adjustment method

(3) variation of mechanical loss in the driving force output from the engine in its delivery to the roller surface.

Table 2 Electric inertia evaluation result

Item	Measurement value	Acceptable range	Judgement
Driving force deviation rate	4.2	5% or lower	Pass
Correlation coefficient	0.9881	0.98 or higher	Pass
Tilt of regression line	1.0033	1.00 +/- 0.02	Pass
Intercept of regression line	-0.81	+/-20N	Pass

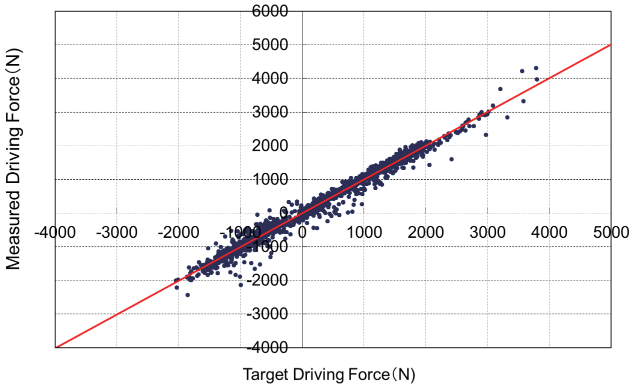

Figure 4 Electric inertia evaluation result

In this section, each of these items was examined based on the measurement data.

Chassis dynamometer stability

If the chassis dynamometer control is unstable, it is possible that the wheel work would be unstable even under the same driving conditions. The degree of change over time was checked by recalibrating the load cell as the stability of the load cell delivers a large effect on chassis dynamometer control but no problem was observed. Then the electric inertia simulation, which is an indicator of basic chassis dynamometer performance, was evaluated since the accuracy of electric inertia control affects the results of such types of chassis dynamometers[5, 6]. It was confirmed that the chassis dynamometer performance satisfied all of the judgment criteria for electric inertia control performance and that there was a high 1:1 correlation between the target vehicle driving force and the actual measurement value[3, 4]. Based on the results in Table 2 and Figure 4, it was concluded that instability of chassis dynamometer was not the cause of the observed variation.

Analysis of force from engine to chassis dynamometer

Figure 5 shows the relationship of the forces in various parts of the vehicle and chassis dynamometer and how the forces are consumed until the driving force generated by the engine is absorbed by chassis dynamometer when the vehicle operates at a constant speed. The driving force generated in the engine is partially consumed by the mechanical components inside the transmission system until it reaches the six-component wheel force meter (which is called transmission system loss). The wheel driving force, detected by the six-component wheel force meter, is transmitted to the roller surface via the tire. The force of the tire driving the roller surface is partially consumed in turning the chassis dynamometer roller (called tire loss), and further absorbed by the power absorbing process of the chassis dynamometer (called dynamometer control running resistance force). The chassis dynamometer also has an internal inherent mechanical loss (called dynamometer parasitic loss). The relationship of these forces is shown below:

Transmission system loss = engine driving force – wheel driving force

Tire loss = wheel driving force – roller surface force

Dynamometer parasitic loss = Roller surface force – dynamometer control running resistance force

The running resistance setting for the chassis dynamometer adjusts the dynamometer running resistance force to match the target running resistance with the vehicle loaded on the roller. Therefore, the dynamometer running resistance force is adjusted to the value obtained by subtracting the vehicle transmission system loss and the tire loss generated between tire and roller from the target running resistance. In this article, the total value of the transmission system loss and tire loss is called the Vehicle Loss.

The actual running resistance force of the chassis dynamometer is the sum of dynamometer control running resistance force and the actual Vehicle Loss.

Vehicle Loss = transmission system loss + tire loss

Actual running resistance force of chassis dynamometer = Dynamometer control running resistance force + Vehicle Loss

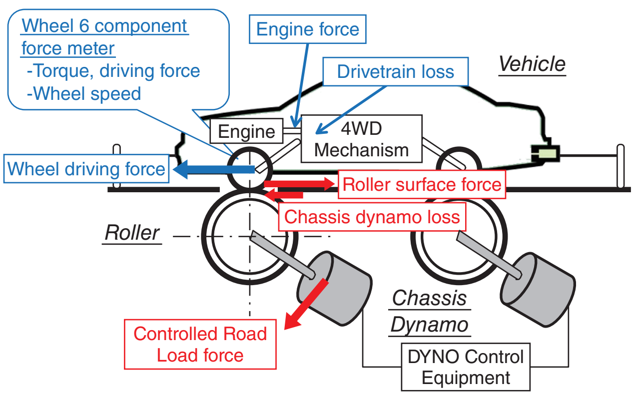

Figure 5 Relation of Vehicle and Chassis Dynamometer

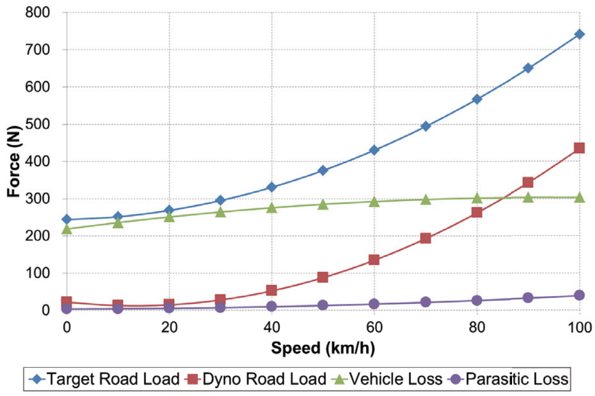

Figure 6 Relation of Road Load and Vehicle loss

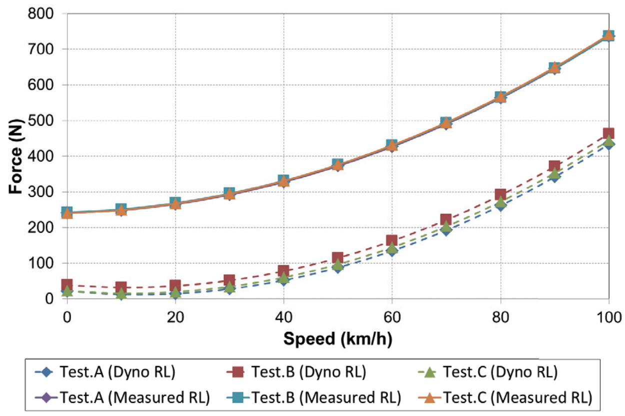

Figure 8 Comparison of Road load

Relationship of forces in the 4WD chassis dynamometer

Figure 6 shows the relationship among target running resistance force, dynamometer control running resistance force and Vehicle Loss after completion of running resistance adjustment. It is evident that there was little effect of windage loss at speeds 40 km/h and lower, with most of the running resistance being Vehicle Loss[3, 4]. In addition, the Vehicle Loss becomes larger in 4WD chassis dynamometer tests as the number of tires in contact with the rollers is twice that of a test using 2WD chassis dynamometer. Thus the effect of Vehicle Loss is much larger in 4WD chassis dynamometer tests. It is also evident that the mechanical loss in chassis dynamometer (Dynamometer parasitic loss) remains small over the entire velocity range.

Fluctuation in work

It was found that the wheel work varied in the 3 mode driving tests (Test A, Test B and Test C) of RL1. A comparison was made by classifying the work into dynamometer work calculated from roller surface force and velocity and Vehicle Loss work. The results are shown in Figure 7[3, 4].

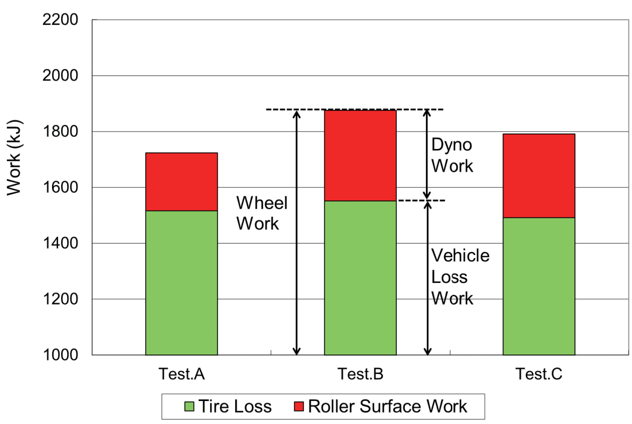

Figure 7 Wheel work breakdown

The value obtained by subtracting the dynamometer work from the wheel work was considered the Vehicle Loss work. It is evident that the difference in wheel work is mainly the difference in dynamometer work. There were also small differences in tire loss work. Since running resistance adjustment had been implemented before conducting these tests, the actual running resistance force and dynamometer control running resistance force were compared immediately after running resistance load adjustment in RL1. The results are shown in Figure 8. It shows that the dynamometer control running resistance force varied, while the actual running resistance including both vehicle and chassis dynamometer matched well. As the chassis dynamometer itself has been proven to be stable, it is therefore assumed that the difference in Vehicle Loss during running resistance adjustment caused the dynamometer control running resistance force to vary as a consequence.

Furthermore, as the wheel work itself varied, it was assumed that the Vehicle Loss during running resistance adjustment and Vehicle Loss during fuel efficiency test were varying somewhat.

Analysis of Causes of Vehicle Loss Fluctuations

It was found that Vehicle Loss had a large effect on the reproducibility of the fuel consumption test outlined in the previous chapter. Therefore, the fluctuations in Vehicle Loss and their effects were examined.

Experiments on Vehicle Loss fluctuations

Breakdown of Vehicle Loss

To confirm the properties of Vehicle Loss, the contributing elements of Vehicle Loss while the vehicle was operating were examined. The transmission system loss was measured as the loss in the driving system, including the differential and gearbox, with a six-component force meter by operating the vehicle from the roller side at constant velocity control on the chassis

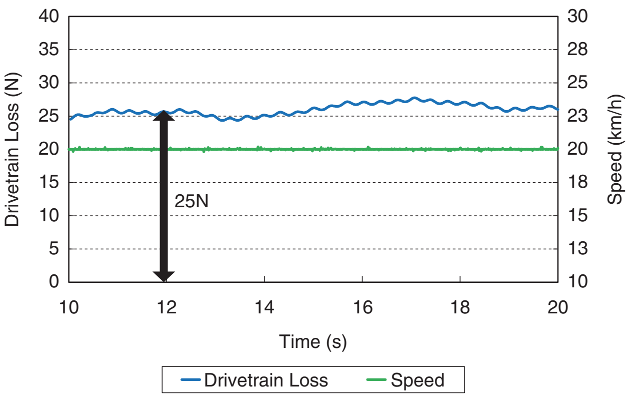

Figure 9 Drivetrain Loss

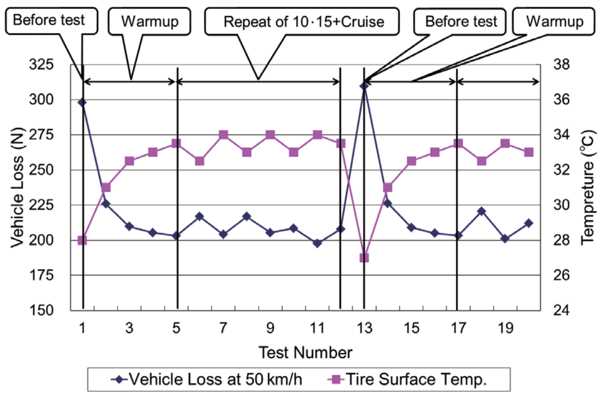

Figure 11 Vehicle loss and Tire surface temp.

dynamometer. Figure 9 shows the measurement results when chassis dynamometer was controlled constantly at 20 km/h. The transmission system loss was approximately 25N[3, 4].

Tire loss was determined by controlling the chassis dynamometer at a constant speed to stabilize the engine inlet manifold vacuum of the vehicle (stable engine driving force) and drive the roller from the vehicle, and measuring the wheel driving force with a six-component force meter. The force absorbed by chassis dynamometer was also measured at the same time. The value obtained by subtracting the absorbed force from the wheel driving force was calculated as the tire loss. Figure 10 shows the results of operation with constant velocity control of chassis dynamometer at 40 km/h and constant engine inlet manifold vacuum of the vehicle[3]. The tire loss when driving was started was approximately 245N, and it is evident that most of the Vehicle Loss is tire loss. It also showed that the tire surface temperature increased by approximately 2 degrees Celsius and tire loss changed (decreased) by 22N after driving for 20 minutes. Based on this, it was decided that the relationship between the tire surface temperature and tire loss should be studied.

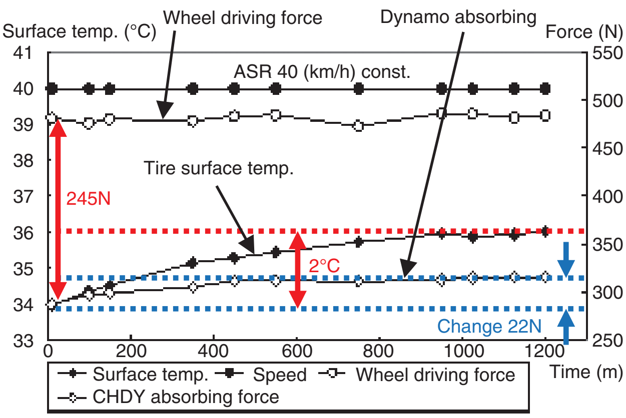

Figure 10 Tire loss behavior

Behaviour of Vehicle Loss and tire surface temperature

An experiment to determine the changes in Vehicle Loss and the tire surface temperature under each mode was implemented using the coast-down method by performing vehicle warm-up driving, 10-15 mode driving and steady speed driving as general test operations. In this section, Vehicle Loss was considered as the value obtained by subtracting the set force absorbed by dynamometer from the measured absorbed force during coast-down. The tire surface temperature was measured on the front tire which was the driving wheel side of the vehicle immediately after completion of operation. To also measure the changes in Tire Temperature and Vehicle Loss while the vehicle was in warm-up mode, its operation at 60 km/h for 10 minutes was repeated 4 times instead of warming up at 60 km/h for 40 minutes. Figure 11 shows the relationship between Vehicle Loss and tire surface temperature at 50 km/h, which is the median velocity value during coast-down test. It is evident that the Vehicle Loss is changed dramatically by the test process and that its behavior shows an inverted trend to the changes in tire surface temperature.

Check on the effects of changes in the tire over time

Whether there was an effect of changes in tire condition (wear) over time as a cause of the changes in Vehicle Loss was confirmed as the overall project was conducted over a long period of time covering the measurements on the test track to the measurements on the chassis dynamometer. As a method of confirmation, changes in Vehicle Loss (Figure 12) were compared starting immediately after installation at steady warm-up at 80 km/h using the tires that were actually used for vehicle testing and brand-new tires[3, 4]. While the Vehicle Loss when the new tire was used was larger than the Vehicle Loss of the tire used in testing immediately their fitting to the vehicle, the difference was nearly eliminated in about 30 minutes. As fuel efficiency tests were conducted after

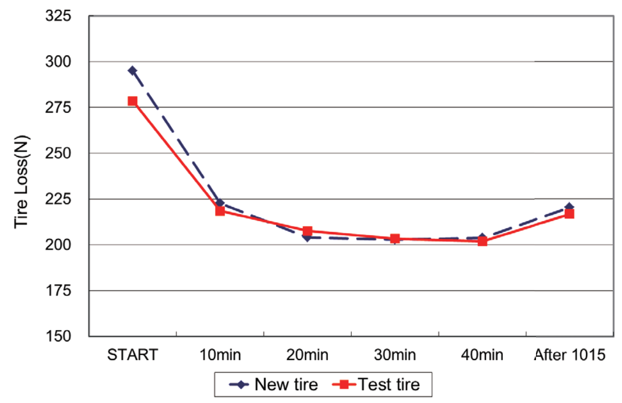

Figure 12 Comparison of Tire

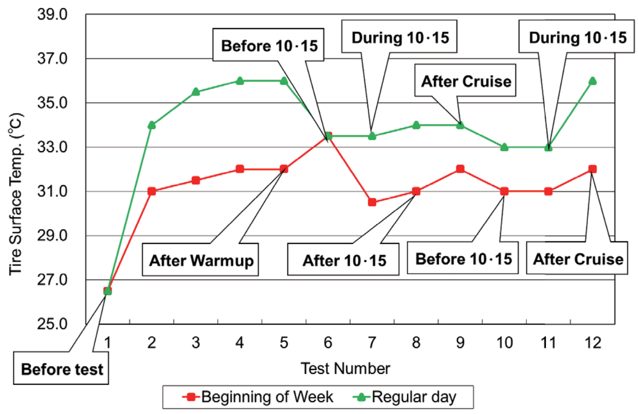

Figure 14 Tire temp. variation for different days

40 minutes of steady warm-up operation, it was considered that there was no effect of changes over time (wear) in the tires used in this experiment.

Cause of fluctuations during running resistance adjustment

In general fuel consumption testing, there are cases when the running resistance adjustment is repeated due to the changes in Vehicle Loss. To determine the changes in actual running resistance during this time, confirmation coast-downs were repeated continuously after running resistance adjustment. Figure 13 shows the values of target running resistance, actual running resistance, dynamometer control running resistance force and Vehicle Loss at the velocity of 50 km/h[3].

If the running resistance adjustment is conducted while the Vehicle Loss is still unstable and large, the dynamometer control running resistance value becomes small. Furthermore, the actual running resistance that is applied on the vehicle also changes clearly when the Vehicle Loss changes due to changes in vehicle temperature and so forth, although the actual running resistance and its target value match immediately after adjustment. Conversely, stable dynamometer control running resistance is delivered and thus the actual running resistance value is also stable when running resistance adjustment is conducted while both the vehicle and Vehicle Loss are stable. Based on these verifications, it was found that the fluctuations in tire loss which mainly comprises the Vehicle Loss need to be controlled and that stabilization of tire surface temperature is extremely important in ensuring the reproducibility of fuel consumption tests.

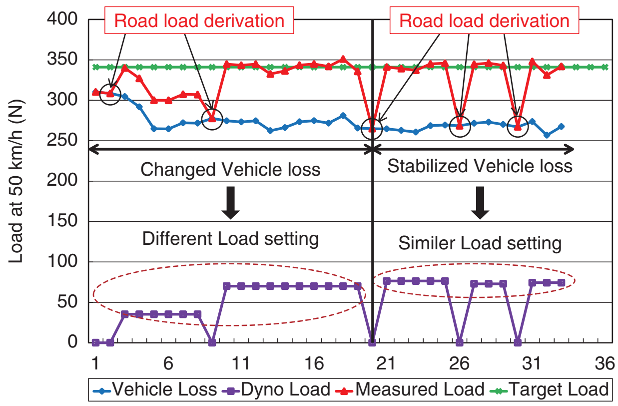

Figure 13 Dynamo Load change by Vehicle loss

Daily fluctuations in tire surface temperature

It was found that the tire surface temperature behaviour changed on a daily basis. As shown in Figure 14, increase in tire surface temperature after starting the test varied dramatically between the first day of testing in the week and subsequent days[3]. It was assumed that this was caused by variation in the Roller Surface Temperature which comes in contact with the tire, as the air conditioning in the chassis room and underground pit was turned OFF for weekends, as well as variation in the method of chassis dynamometer warm-up before testing.

Effect of roller temperature

The part of the roller that was best to measure its temperature was first verified. Thus the temperatures of (A) roller surface, (B) roller inside edge and (C) roller side edge as shown in Figure 15 were measured to check the temperature changes after the test was started[4].

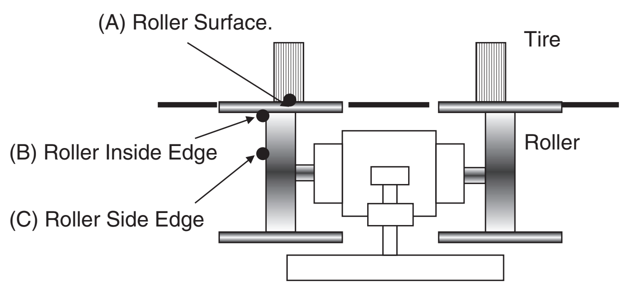

Figure 15 Roller temp. measurement point

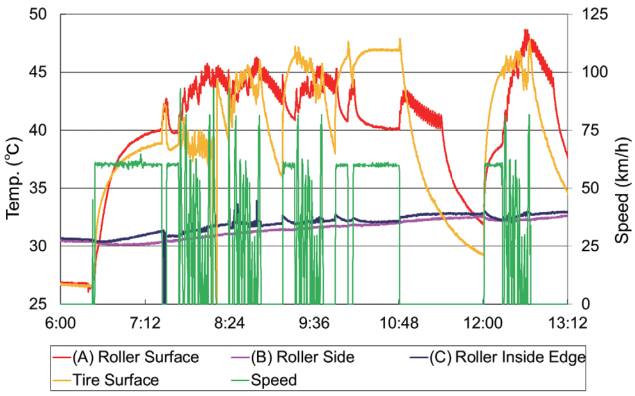

Figure 16 Roller temp. changing

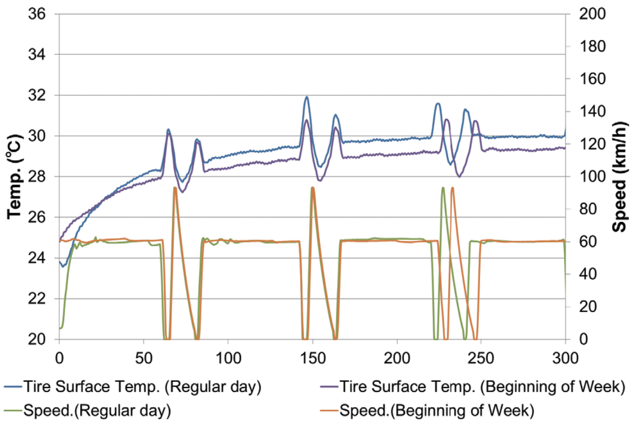

Figure 18 Comparison of Tire surface temp.

Figure 16 shows the temperature changes in these areas. It was decided that the temperature at (B), the roller inside edge, should be observed as a point where the temperature changes in the roller itself can be measured with little effect of the tire surface temperature changes or a cooling airflow.

Based on these results, the conditions at the first test start after the weekend and those following during the week were reproduced to compare the Roller Temperature increase under these conditions. Figure 17 shows the results. It is evident that the Roller Temperature increased in a different manner.

Therefore, the tire surface temperature and the amount of Roller Temperature increase were compared between the two cases. Figure 18 shows that the tire surface temperature varied, and Figure 19 shows that it was caused by the difference in Roller Temperature. Based on this, it was evident that the tire surface temperature was low in the first test of the week because the Roller Temperature was low, and that the Roller Temperature did not increase significantly by the normal roller warm-up. It is thus surmised that the fact that the tire surface temperature does not increase as much because of the Roller Temperature, influences the tire loss greatly. It is assumed that this is the cause of higher fuel consumption results in tests conducted after the weekend, which had been talked about for many years.

How to improve the effect of Roller Temperature. It was found that the condition of Roller Temperature at the beginning of the test differed when test was started after a weekend as the air conditioning had been turned OFF in chassis room and underground pit. As a measure to improve this matter, a case in which the underground pit temperature was controlled at 30 degrees Celsius by air conditioning on weekends was compared. Based on the results in Figure 20, it was found that the Roller Temperature behavior at the beginning of test after weekends was closer to those at the beginning of tests during the week. Therefore it is important to manage the Roller Temperature at the beginning of test.

Discussion about roller warm-up

Normally, the warm-up of the chassis dynamometer is

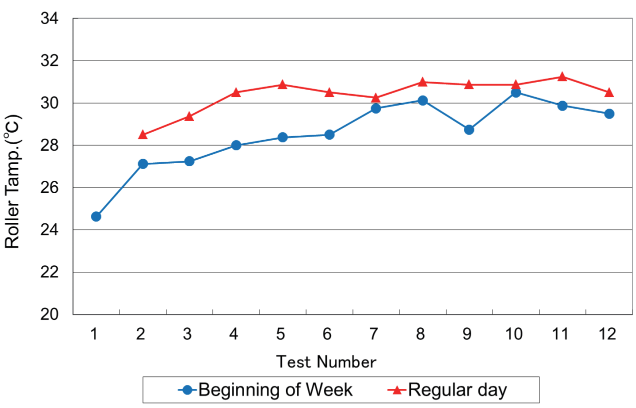

Figure 17 Roller temp. for different day

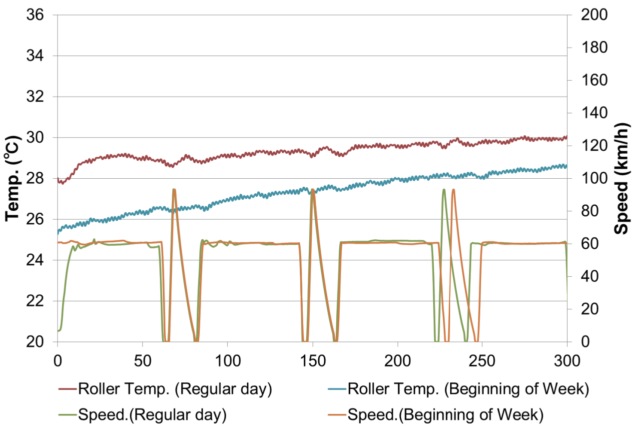

Figure 19 Comparison of Roller temp.

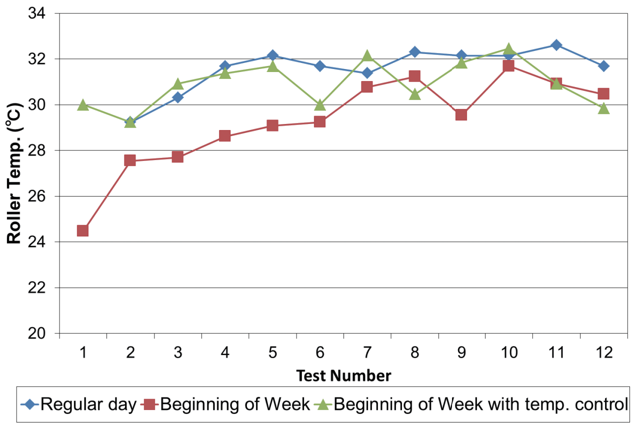

Figure 20 Roller temp. by pit temp. control

performed on the actual chassis dynamometer itself. Therefore, the Roller Temperature was compared between the case in which chassis dynamometer is warmed up by itself and the case in which it is warmed up using a vehicle. Figure 21 shows the results. The Roller Temperature does not increase when the warm-up operation is performed by the chassis dynamometer itself. It only increases when chassis dynamometer warm-up operation is conducted using a vehicle. Therefore, increasing the Roller Temperature by conducting chassis dynamometer warm-up by operation of a vehicle (obviously not the test vehicle) after weekends would be an effective method.

Conclusion

It was confirmed in fuel consumption tests on 4WD chassis dynamometer that the differences in Roller Temperature and tire surface temperature affect the Vehicle Loss and ultimately the wheel work and fuel consumption. The following conclusions have been reached:

- Tire loss, which comprises most of the Vehicle Loss, is affected dramatically by the Tire Temperature and varies depending on the operating conditions.
- When running resistance adjustment is conducted before the Vehicle Loss (including tire loss) stabilizes, the chassis dynamometer is not adjusted properly and this affects the fuel consumption.
- Even if the vehicle and tire surface temperature are stable, the Vehicle Loss is affected by large differences in Roller Temperature and thus fuel consumption is also affected.

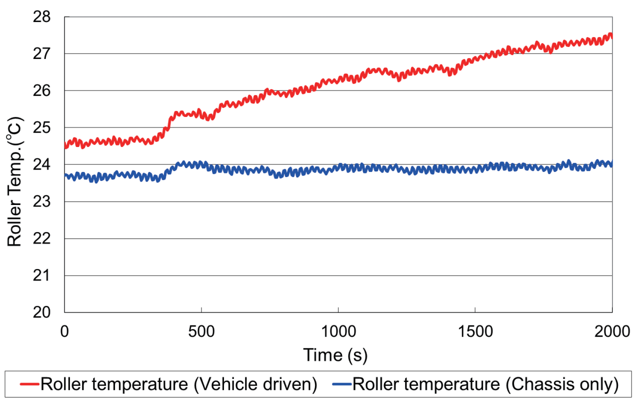

Figure 21 Roller temp. different by Warm-up

As demonstrated above, it was confirmed that the stabilization of Roller Temperature on the chassis dynamometer is important in fuel consumption tests , in addition to vehicle stability. As an issue for the future, it is necessary to define or control the environmental conditions, warm-up conditions etc to provide stable results.

Finally, a photograph of our latest 4WD chassis dynamometer (VULCAN EMS-CD48L 4WD) is shown below.

Figure 22 VULCAN EMS-CD48L 4WD

HORIBA developed and introduced an electric inertia simulation type twin-axle roller chassis dynamometer in 1980. In 1991, we delivered an electric inertia type single axle, 48-inch (1219.2 mm roller diameter) chassis dynamometer for 2WD vehicles to the U.S. Environmental Protection Agency (EPA), where it was adopted as the standard type of chassis dynamometer for North America. An electric inertia type twin-axle, 48-inch chassis dynamometer for 4WD vehicles was also delivered in 2004. Domestically, HORIBA has participated in the examination of the electric inertia simulation method[5, 6], which was used for evaluation of the basic performance of chassis dynamometers in this article and also used for the establishment of chassis dynamometer standards. The current VULCAN EMS-CD48L Series has been developed from this historical background and the application of our knowledge and experience.

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