Special Feature: Drivetrain and Braking Technology

Research Report

On-board Estimation of Vehicle Weight and Its Application to an Engine Brake Control System

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ABSTRACT In some vehicle dynamic control systems, it is important to control based on the vehicle weight without the need for special sensors. Especially, in commercial vehicles having great variations in load capacity, improvements in engine brake performances are significant issues for vehicles with an automatic transmission (AT) in terms of both safety and performance. When we use physical models to estimate something, we have to provide estimates for two or more unknown parameters. In addition, since such a method is influenced by disturbances in the measured signals, it is difficult to maintain an acceptable level of accuracy. So, after analyzing the physical phenomena, we developed a new method that eliminates the influence of the disturbances from the measured signals and constructed an estimation system that has a minimum number of unknown parameters that was capable of providing a more accurate estimate of a vehicle weight. This method was applied to the engine brake control of a 6-speed AT for commercial vehicles and its efficacy was verified.

KEYWORDS Vehicle Weight, Estimation, Road Gradient, Engine Brake Control, Automatic Transmission

1. Introduction

The engine brake control,(1) by which the gear ratio is automatically changed according to an estimate of the gradient, has been normally offered on many models of passenger cars to provide a solution to the problem of insufficient engine braking. The value of the gradient, needed for the engine brake control, is generally estimated using a longitudinal equation of motion and calculating the acceleration and the driving force. It is assumed, however, that the vehicle weight is constant. A change in the vehicle weight has a relatively small effect on the estimate of the gradient in the case of a passenger car because the change is relatively small. In the case of a commercial vehicle, however, an accurate value for the vehicle weight is necessary as this value can change considerably depending on whether the vehicle is loaded or empty. Engine brake control has not become as popular in commercial vehicles, however, given the costs incurred for providing the required sensors. Therefore, many commercial vehicle users still resist using engine brakes with commercial vehicle ATs, such that manual transmissions (MT) remain more popular. **Figure 1** shows the driver's workload when going uphill and downhill. In the case of an AT vehicle, the brakes must be applied more often than with an MT vehicle, making the driver's workload higher. To overcome this, the advantage of an AT – freedom from manual gear changes – can be leveraged by optimizing the engine brake force so as to make the driver's workload more closely resemble that of an MT vehicle, which would improve the safety of the AT vehicle.

One proposed method of estimating the vehicle weight(2) deletes the paragraph for the gradient from the equations that assume the gradient to be constant by using two longitudinal equations of motion

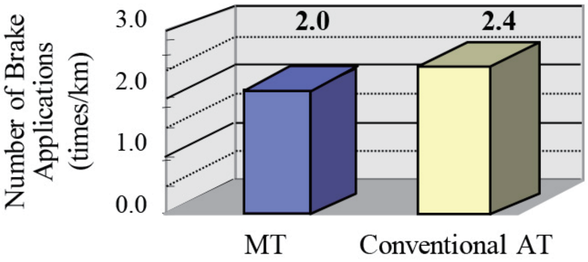

Fig. 1 Driver's workload going uphill and downhill.

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between two different points in time to estimate the vehicle weight. There is a problem with this approach, however, in that the estimation accuracy deteriorates when the change in the gradient is large. Moreover, there are problems of high cost and the durability and reliability of the sensor, although it is possible to install load sensors in each suspension unit to measure the vehicle's weight. In this work, we aimed to estimate the vehicle weight accurately without a cost increase. Specifically, the new method removes the frequency component from the estimation signal for the gradient, based on a universal difference in a time change in the gradient that is an unknown parameter in the equation of motion, driving force and the acceleration of the vehicle. We verified, by experiment, that a highly accurate estimate of the vehicle weight can be obtained. Moreover, we examine the application of the method to the braking force control for a commercial vehicle, which would reduce the driver's workload.

2. Estimation of Vehicle Weight

Vehicle weight is estimated using the equation of motion for longitudinal movement given by Eq. (1) which derived from driving force F and the acceleration α shown in **Fig. 2**. And, the road gradient θ can be calculated as Eq. (2).

$$\frac{W}{g}\alpha = F - W\sin\theta - Fr \qquad (1)$$

$$\sin\theta = \frac{F - Fr}{W} - \frac{\alpha}{g} \qquad (2)$$

W : Vehicle weight
g : Acceleration due to gravity
α : Vehicle acceleration
F : Driving force
Fr : Sum of an air resistance and a rolling resistance

2. 1 Significance of Estimating Vehicle Weight

Figure 3 shows the sensitivity for the estimation error of the gradient to the change in vehicle weight when estimating the gradient by Eq. (2). Assuming that the vehicle weight is 2000 kg, the estimation error for the gradient rises to as much as 200% for a commercial vehicle due to the fact that the vehicle weight can change by about ±50%. On the other hand, the maximum error for a passenger car is only about 30%, as its weight only changes by about ±10%. From this point of view, weight estimation is very important in the case of a commercial vehicle.

2. 2 Primitive Equation for Vehicle Weight Estimation

Next, a primitive equation for estimating the vehicle weight is derived, and the problem to solve is clarified. In Eq. (1), considering a general AT, the driving force is given by turbine torque Tt given by Eq. (3). Tt can be calculated according to the torque converter characteristics (**Fig. 4**), determined by the speed ratio (Nt/Np),

$$Tt = t \cdot C \cdot Np^2, \qquad (3)$$

where t and C are the torque ratio and coefficient of capacity, respectively. Alternatively, the turbine torque

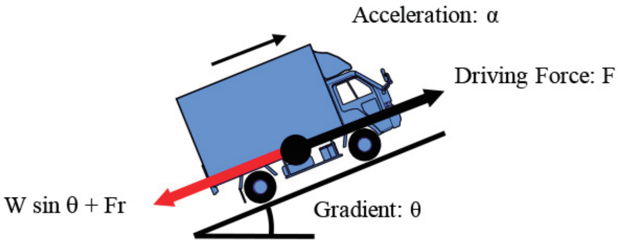

Fig. 2 Longitudinal movement of vehicle.

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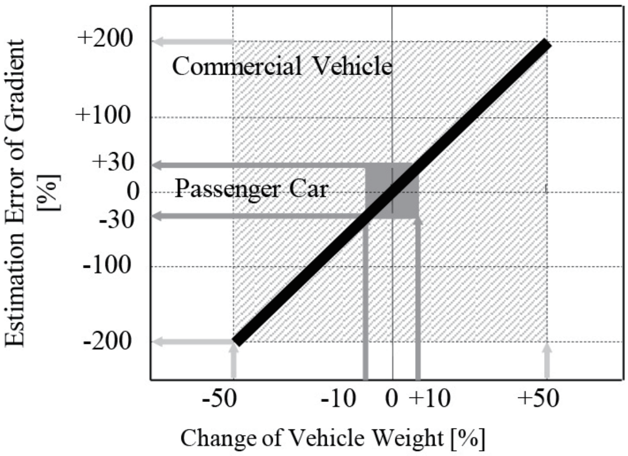

Fig. 3 Influence of error in weight estimation.

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can be expressed in the rotational equation for the engine (Eq. (4)) while the hydraulic torque converter is locked-up.

$$\left.\begin{aligned} Tt &= Te - Ie\,\frac{d\,Ne}{d\,t} \\ Te &= fn\,(\,Ne,\,\Theta\,) \end{aligned}\right) \tag{4}$$

Te is the engine torque represented by the function fn for the engine rotational speed Ne and throttle opening Θ. Ie is the entire rotational inertia of the engine and hydraulic torque converter.

Therefore, multiplying Eq. (3) or Eq. (4) by the AT gear ratio γ and the final gear ratio λ gives the driving force F generated by the tire,

$$F = \gamma\,\lambda\,Tt\,/\,rt\,, \tag{5}$$

where rt is the effective radius of the tire.

The vehicle weight can be estimated using Eq. (6) by transforming Eq. (1) and using the estimate value of the acceleration α given by the difference in the output rotational speed of the AT and estimating the value of the driving force F obtained from Eq. (5).

$$\hat{W} = \frac{\hat{F} - \hat{Fr}}{\hat{\alpha}\,/\,g + \sin\theta} \tag{6}$$

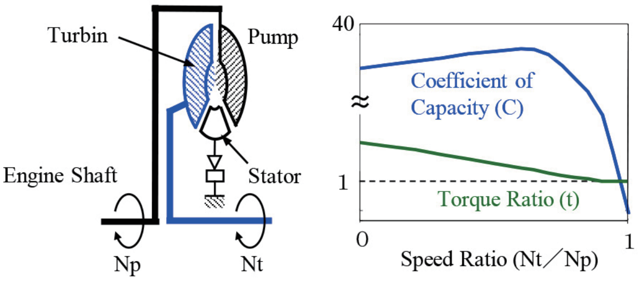

Fig. 4 Torque converter characteristic.

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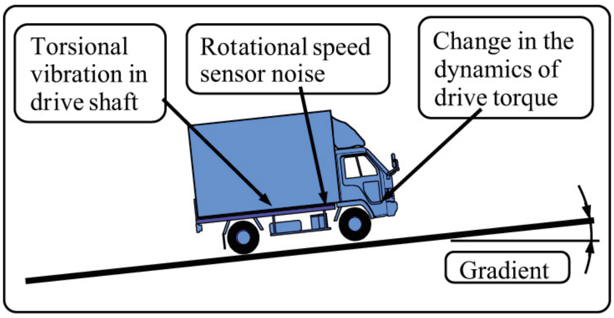

Fig. 5 Disturbances in estimating vehicle weight.

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With Eq. (6), however, it is necessary to remove the influence of the gradient because the gradient θ is also an unknown parameter. Moreover, because disturbances (**Fig. 5**) are incorporated in the rotational speed signals used for the estimation, it is important for the improvement of estimation accuracy to minimize those influences. Other than the gradient, the disturbances include torsional vibration in the drive shaft, delay or dead time in the driving force signal and detection errors included in the rotational speed signal.

2. 3 Principle of Estimation

Vehicle weight is estimated as only the unknown parameter by removing the influence factors described by section 2. 1, as follows.

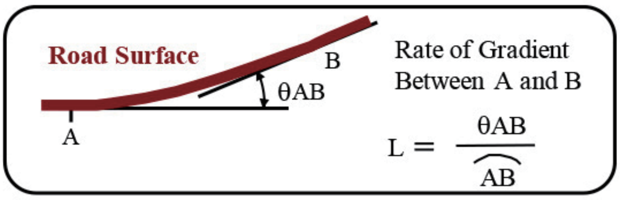
2. 3. 1 Removal of Gradient Influences

The change specification of the gradient is laid down by law from the viewpoint of safety of the occupants and vehicle, as shown in **Table 1.** Although this law was formulated by the Japan Road Association, legislation around the world is very similar.

Figure 6 shows the situation where the driver steps on the accelerator pedal when approaching the gradient and running at about the twice the design

Table 1 Specification of change of road gradient.

V: Design Speed [km / h]	40	80	120
L: Rate of Gradient [% / m]	0.230	0.056	0.025



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speed on a sloping road with the rate of gradient for 40 km/h in the design speed of Table 1. A power spectrum density of the weight gradient resistance, that is, W$\sin\theta$ in Eq. (1), an accelerating force and driving force are shown in **Fig. 7** under these conditions. The acceleration and driving force have a frequency element of 1 Hz or more although the weight gradient resistance has few frequency elements in excess of 1 Hz. **Figure 8** shows the power spectrum density for the change in the gradient when running at up to two times the design speed on a sloping road with the profile shown on the left side of Fig. 8. The power at more than 1 Hz is as small as that shown in Fig. 7. Therefore, it is universally recognized that the change in the gradient is more gradual than the change in the acceleration signal or driving force signal. So, by using this universal phenomenon, the vehicle weight can be estimated without the influence of the gradient by removing the frequency elements of 1 Hz or less from the acceleration and the driving force signal calculated by Eqs. (5) and (6). In the result, it is possible to estimate using Eq. (7).

$$\hat{W} = \frac{\hat{F} - \hat{Fr}}{\hat{\alpha}/g} \qquad (7)$$

2. 3. 2 Removal of Powertrain Torsional Vibration

Changing the driving force usually leads to torsional vibration in the drive shaft connected to the output shaft of the AT, because the torsional stiffness is low. In **Fig. 9**, the acceleration can be seen to vibrate

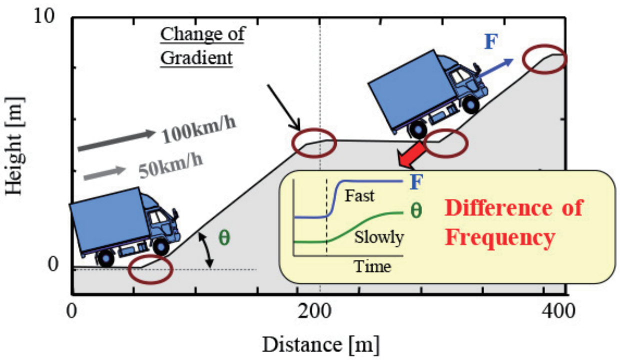

Fig. 6 Road surface profile.

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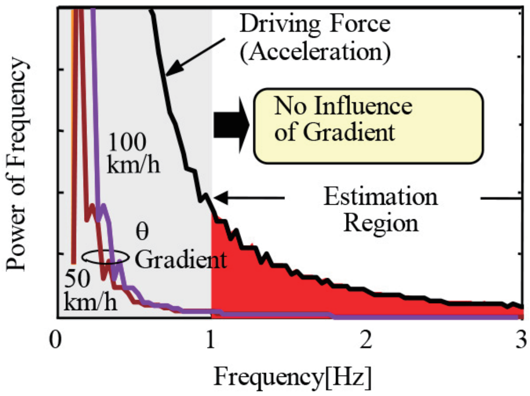

Fig. 7 Frequency characteristic of change of road gradient (simulation).

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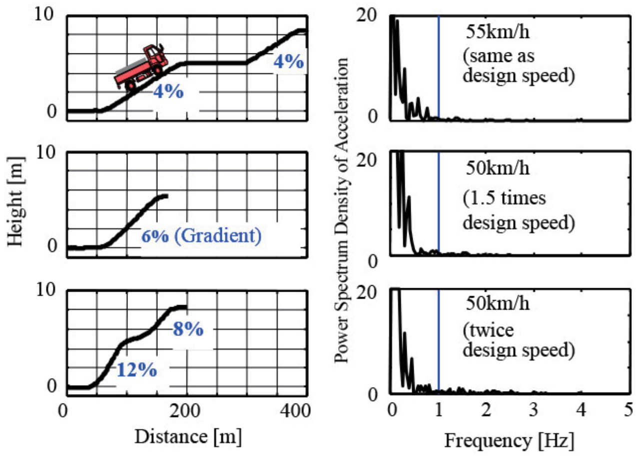

Fig. 8 Frequency characteristic of change of road gradient (experiment).

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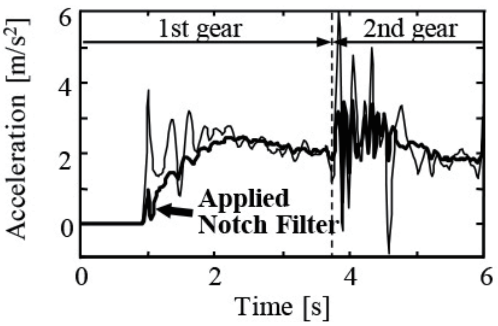

Fig. 9 Elimination of torsional vibration from acceleration signal.

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slightly because this torsional vibration influences the output rotational speed signal of the AT. By analyzing the power spectrum density of this vibration, we find that it has a strong frequency element of about 3 Hz as shown in **Fig. 10**, above. Then, by applying a notch filter as shown in the lower part of Fig. 9, we can obtain the acceleration signal at which the torsional vibration is reduced, as shown by the heavy line in Fig. 10.

2. 3. 3 Removal of Dynamics of Driving Force

If there is neither a gradient nor running resistance and the true value of vehicle weight is known, the shape of the waves of the driving force signal and the accelerating force signal calculated by Eqs. (5) and (6) should correspond to each other. However, their phases will not correspond due to the dynamics caused by the torsional stiffness of a shaft or the deformation of a member because the driving force is calculated at the output of the torque converter, that is, the input to the AT and the acceleration are calculated at the output of the AT. Moreover, since the rotational speed when starting has no effect on the detection accuracy of the rotational speed sensor, the rise times of the driving force and acceleration do not correspond. Therefore, if the vehicle weight is estimated in real time, the estimation will not be stable and the estimation error will be large due to the disagreement of the phase. However, both shapes are similar, as shown in **Fig. 11**, so a method for keeping the discrepancy of the phase to a minimum by using both time integration values (shaded portion), that is, integrating the numerator and the denominator in Eq. (7) respectively and estimating the vehicle weight given by Eq. (8) was devised.

$$\hat{W} = \frac{\int (\hat{F} - \hat{Fr})\,dt}{\int \hat{\alpha} / g\,dt} \tag{8}$$

2. 4 Construction of Weight Estimation System

An estimation system that converts vehicle weight into a unique unknown parameter by removing the disturbance factors from the vehicle weight estimation described in section 2. 2 was constructed as shown in **Fig. 12**.

The pump, turbin and output speed are filtered with a low pass filter to remove noises at high frequency region, respectively. Driving force is calculated using

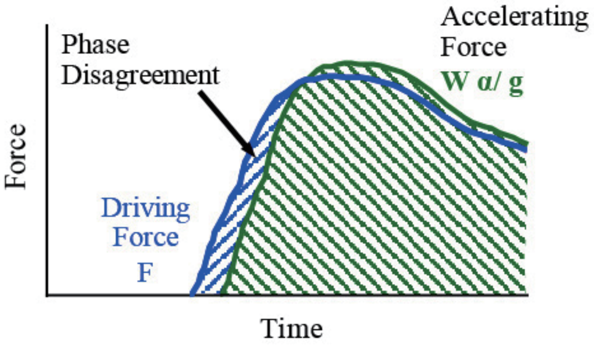

Fig. 11 Dynamics of drive force and acceleration.

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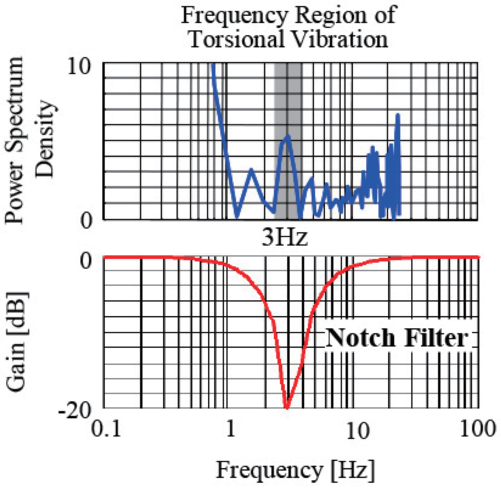

Fig. 10 Frequency characteristic of torsional vibration in acceleration signal.

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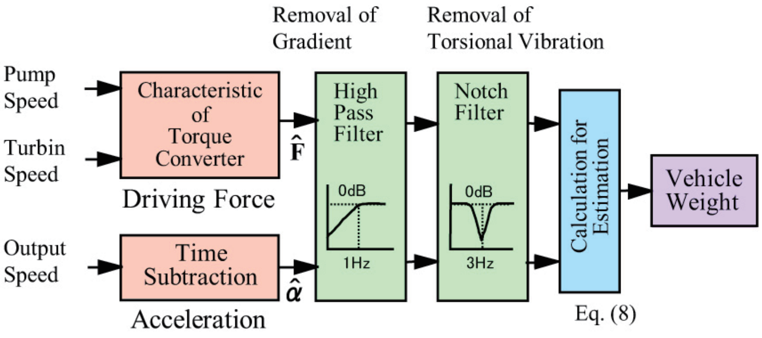

Fig. 12 Construction of weight estimation system.

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Eq. (5), and the acceleration is calculated according to the time subtraction of the output rotational speed of the AT. Both signals are integrated relative to time through the high-pass filter that removes the gradient, and through the notch filter that removes the torsional vibration. Then the vehicle weight is estimated by Eq. (8). The data sampling time is set to 50 ms, therefore about 50 data points are used to calculate the vehicle weight, for example, when the data is shown in Fig. 9 and the calculation is implemented from just after the start to just before the shift.

2. 5 Estimation Result On-the-road Experiment

Because the influence of the gradient can be removed effectively, it is preferable that the change in the driving force and the acceleration is large. **Figure 13** shows the comparison of the driving force when starting and stepping on the accelerator. Starting features a larger change in the driving force. Then, the estimate is implemented once every time the vehicle starts by using the signals of the driving force and the acceleration between the first gear and the second.

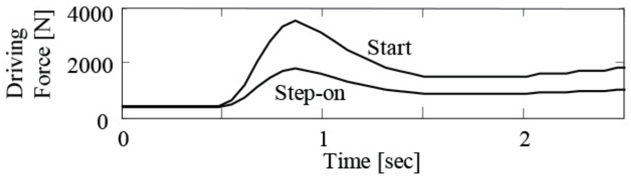

Fig. 13 Driving force for start and step-on.

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Figure 14 shows the results of verifying the effect of the filter processing explained in section 2. 3. 1 when a truck having an empty weight of about 2.8 t starts twice from an upward gradient, a flat road, and a downward gradient, respectively, when empty and when carrying 1 t. The error in the estimation falls to within 15% with the filter processing, that is, the method shown in Fig. 12 for removing gradient, while without the filter processing the error is 50% or more, such that we can see the effectiveness of removing the influence of the gradient.

Figure 15 shows the estimation result (20 times) using the method shown in Fig. 12 for each start when running on a typical road from flat, to an upward gradient and a downward gradient. The actual vehicle weight is about 3.8 t. The figure indicates that the estimation accuracy of the progressive average after eight starts is within 5% even though there is some variation in each estimate.

3. Application to Braking Force Control

Figure 16 shows a braking force control system that uses vehicle weight and the gradient that is calculated based on the vehicle weight estimate. The deceleration demanded by the driver beforehand according to the calculated gradient is requested from the velocity of the car, the control execution switch and the braking operation, the best braking actuator is selected, and the braking force is controlled. In Fig. 16, the gradient can

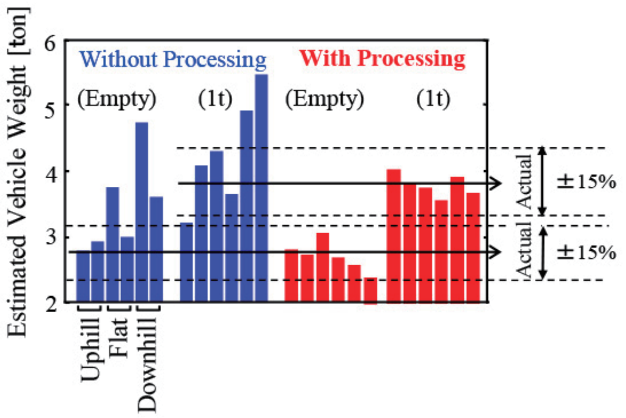

Fig. 14 Effectiveness of signal processing.

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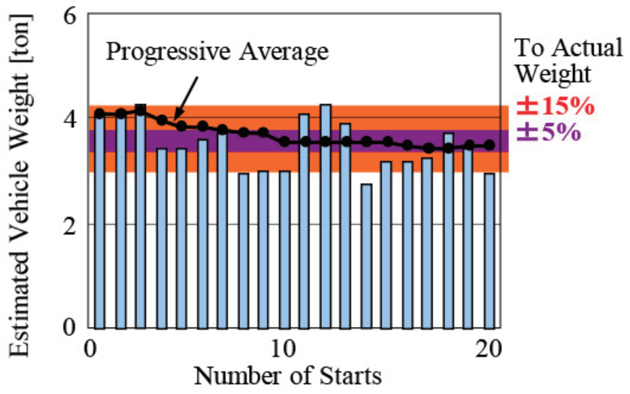

Fig. 15 Result of estimating weight.

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be calculated from Eq. (9) by using the driving force, acceleration after the notch filter in Fig. 12 and the estimated vehicle weight.

$$\sin\theta = \frac{\hat{F} - \hat{F}r}{\hat{W}} - \frac{\hat{\alpha}}{g} \qquad (9)$$

Figure 17 shows one example of the results of calculating the gradient. The calculation result almost corresponds to the measured real slope although the error margin is a little large because the real slope is calculated every 100 M above sea level to give an average slope.

Increased number of gears and capability for torque converter clutch to engage at a low speed are essential to providing the deceleration rate desired by drivers. Increased number of gears enable changes in deceleration rate between gears to decrease. This is important for the system to attain driver's desired deceleration rate in various driving conditions. Also, increased number of gears help to allow the torque converter clutch to stay engaged in lower vehicle speeds. **Figure 18** shows the structure of the torque converter clutch. The architecture of the pressure supply path to the clutch is different from that of pressure supply path to the torque converter. This architecture was adopted to ensure that the torque converter clutch could be engaged independent of internal torque converter pressure. In addition, to allow increased responsiveness, a multi-plate clutch pack is adopted as the clutch architecture. By implementing this architecture and utilizing continuous slip control, the torque converter can stay engaged at lower vehicle speeds (down to approximately 20 km/h).

Figure 19 shows an example of the comparison between the deceleration rates desired by drivers and the engine brake performances for a 6-speed AT and a 4-speed AT. In the case of a 4-speed AT, the vehicle deceleration was outside the range of the deceleration desired by drivers at 40 km/h vehicle speed for the reason that the lock-up clutch turns OFF. On the contrary, in a 6-speed AT, increased number of gears and shifting of the lock-up clutch down to lower speeds provide a

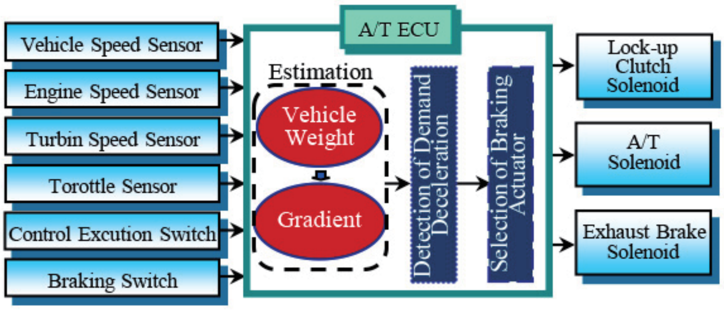

Fig. 16 Structure of braking force control.

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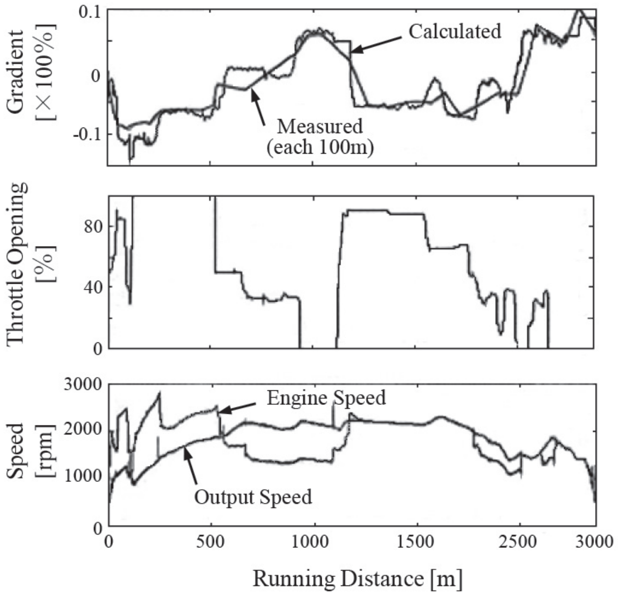

Fig. 17 Result of estimating gradient.

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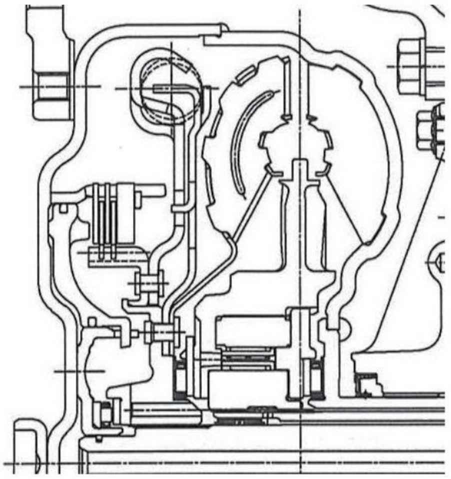

Fig. 18 Lock-up clutch of torque converter.

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smooth rate of the deceleration desired by drivers from high to low (20 km/h) vehicle speeds.

Figure 20 shows the result of verifying the effect of the braking force control shown in Fig. 16 on suburban and town roads. We confirmed that this control reduces the braking frequency to a level less than that of an MT vehicle and decreases the driver's workload relative to an AT vehicle (no control).

Figure 21 shows comparison of energy absorbed by the brake pad. It shows significant differences by utilizing the brake control and can be concluded that the brake control contributes to extending brake pad life.

4. Conclusion

We have developed a new method for estimating the vehicle weight without the need for special sensors.

- A universal difference always appears in the frequency element of the acceleration, driving force change and gradient change. A change in the gradient has few frequency elements of more than 1 Hz, while the changes in the acceleration and driving force have many of more than 1 Hz.
- We have developed a vehicle estimation system that removes the influence of the gradient, which is an unknown parameter, and other disturbances and that estimates vehicle weight by using time integration.
- In a general on-the-road experiment with a commercial vehicle, this estimation system exhibited an estimated accuracy of ±5% for starts (progressive average after eight starts).

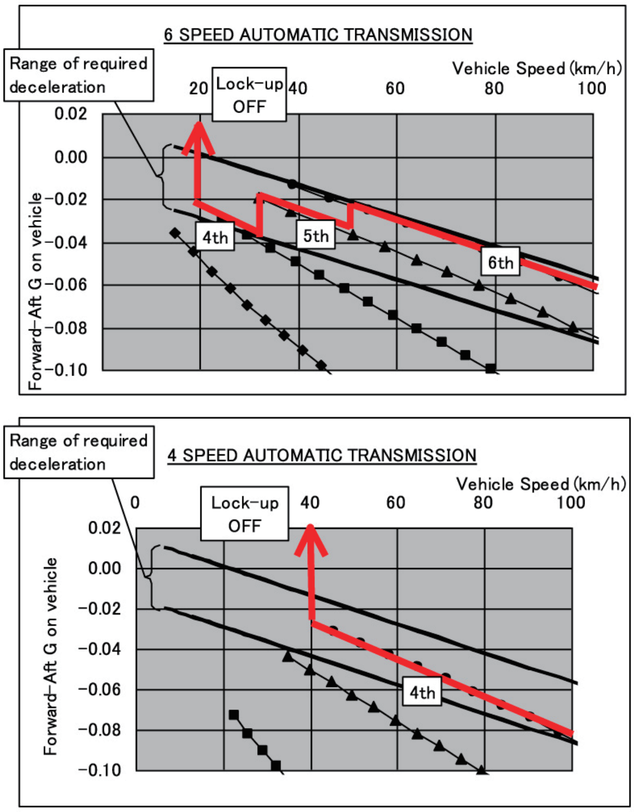

Fig. 19 Desired deceleration and engine brake performance.

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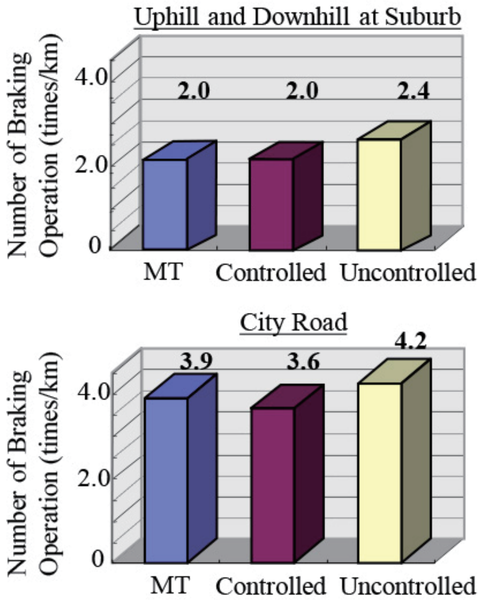

Fig. 20 Result of braking force control.

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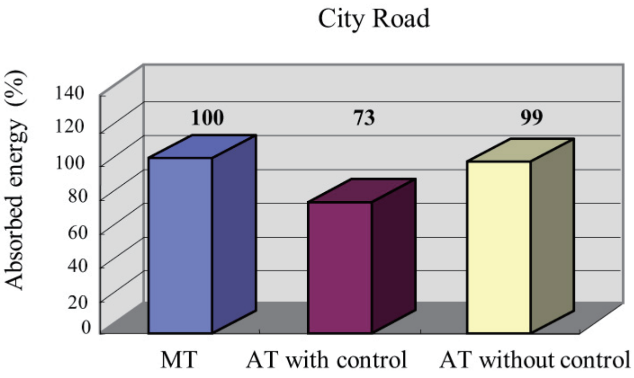

Fig. 21 Energy absorbed by the brake pads.

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- Applying this estimation method to braking force control results in a lower driver's workload.
- This estimation method requires only the acceleration and driving forces that are obtained using speed sensors, allowing it to be easily applied to system control requiring vehicle weight information, such as vehicle motion control or suspension control, etc.

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