Vehicle Simulation-Based Quantitative Evaluation for Power Consumption and Ride Comfort

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Vehicle electrification has been proactively promoted because of environmental restrictions. At the same time, new functions, such as autonomous driving and V2X communication, have made vehicle systems more complex. As the development costs have risen following these trends, system development using simulation has come into widespread use to improve cost efficiency. We have been developing simulation techniques to identify the effects of improvements in our product performance in regard to power consumption. This paper introduces a simulation technique to verify the trade-off between power consumption and ride comfort.

Keywords: automotive, simulation, model-based development

1. Introduction

In recent years, with the tightening environmental regulations around the world, automotive electrification has been actively promoted. At the same time, it is expected that on-board systems will become more complicated with the introduction of automatic driving, vehicle-to-everything (V2X) communication, and ECU reprograming using cellular network. Under these circumstances, shortening the development time of new vehicle models has been an important issue. Therefore, car makers require auto parts suppliers to participate in their development process of creating specifications and drawings, and to make suggestions not only on components but also vehicle systems. As a development method used here, attention has been focused on "model-based development,"(1) which contributes to a shortened development period, and it is becoming essential to adapt the method.

In order for the parts suppliers to meet those requirements, the Advanced Automotive Systems R&D Center has been engaged in the development of simulation techniques for verification of the performance of our products. We have developed a technique to analyze how our electrical products affect fuel consumption up to 2016,(2) and this technique is currently being used to analyze power consumption of electric vehicles. With electric vehicles, there is trade-off between power consumption and ride comfort, both of which are important factors for creating appealing vehicles. Therefore, it is necessary to evaluate power consumption and ride comfort at the same time. Conventionally, sensory evaluation using prototype vehicles was carried out to evaluate ride comfort. However, in order to conduct a parametric study on the trade-off at the design stage, we quantified the ride comfort, made a model, and implemented it into simulation. This paper introduces the simulation technique for the quantitative evaluation of power consumption and ride comfort.

2. Quantify Ride Comfort

With electric vehicles, acceleration and deceleration affect not only ride comfort but also power consumption. For example, in the case of regenerative brake,*1 to improve the power consumption, it is better to maximize regenerative power as soon as possible. However, rapid deceleration throws the head and body of passengers forward, causing them discomfort. Considering the appeal of the vehicle, we should restrict the acceleration for ride comfort. The restriction of acceleration affects component specifications such as the power consumption and power generation of a motor. If we can evaluate the ride comfort at the design stage, we will be able to develop more efficient parts by preventing redesign after trial production. For this purpose, it is necessary to quantify the relationship between vehicle movements and ride comfort. This study focuses on the vehicle movement during acceleration and deceleration and quantifies the ride comfort.

2-1 Condition of ride comfort evaluation using real vehicles

Wang et al. worked on quantifying ride comfort using acceleration and jerk*2 as variables.(3) They measured vehicle longitudinal acceleration and the subjects were asked to press switches according to the discomfort degree. Thereby Wang et al. obtained the relationship between the acceleration and discomfort, and between the jerk and discomfort. With reference to this method, we were able to quantify the ride comfort using real vehicles.

We used two vehicles with an electric powertrain,*3 and measured vehicle longitudinal acceleration with an acceleration sensor. Since we cannot measure the jerk directly, we calculated the jerk by differentiating the acceleration and used a low-pass filter*4 to exclude the influence of noise. The evaluation of comfort was based on the following four levels. Three subjects on the passenger seat and the rear seats pressed the switch for evaluation. An overview of the measurement system is shown in Fig. 1.

Level 0: Not uncomfortable. (Do nothing)
Level 1: Slightly uncomfortable (Press Switch 1.)
Level 2: Uncomfortable (Press Switch 2)
Level 3: Very uncomfortable (Press Switch 3)

Twenty men in their 20's to 50's participated in this study. The evaluation was carried out on flat paved roads in Nagoya and Osaka, Japan, and run in a speed pattern that produced various acceleration rates and jerk.

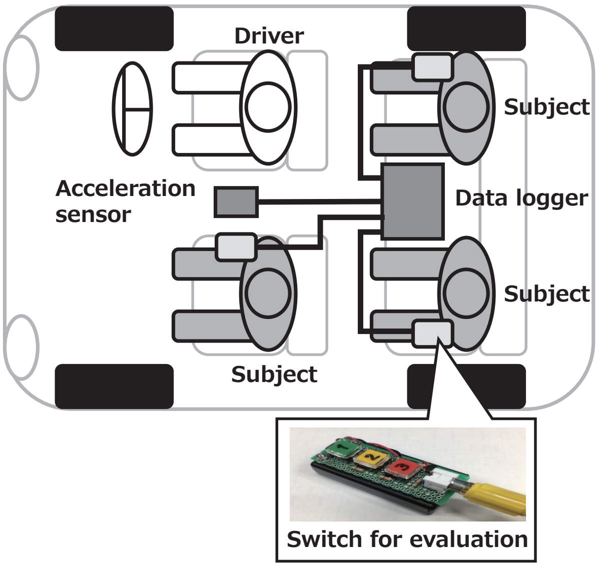

Fig. 1. Overview of the measurement system

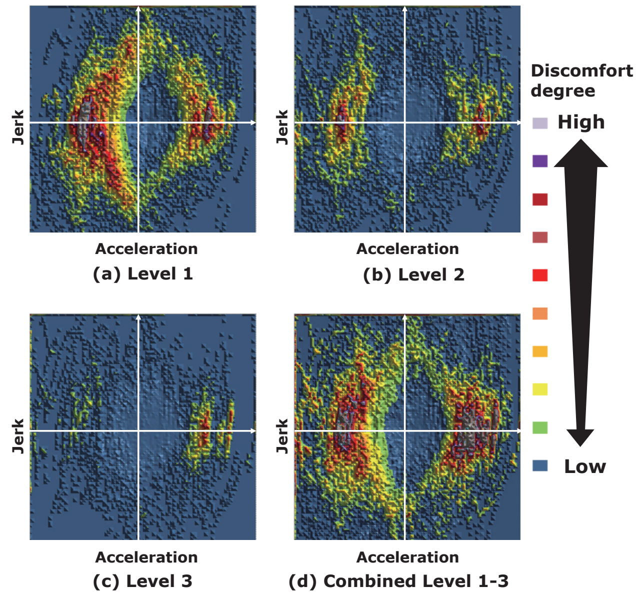

Fig. 2. Discomfort degree map

2-2 Results of the ride comfort evaluation using real vehicles

We mapped the measured values of discomfort with acceleration on the x axis and jerk on the y axis. We calculated the degree of discomfort at each acceleration/jerk point using the following mathematical formula: Discomfort degree = (Frequency that the switches were pressed) / (Frequency of acceleration and jerk). The results are shown in Figs. 2 (a) to (c), and the superimposed result of discomfort at each level is shown in Fig. 2 (d).

The degree of discomfort was higher when the vehicle was decelerated than when accelerated, and the degree of discomfort became high when the jerk was large even if the acceleration was small. These results were consistent with the indication by Wang et al. that the impact on ride comfort was deceleration > negative jerk > positive jerk > acceleration. Therefore, it was considered that reasonable evaluation results were obtained. Sensitivity to discomfort varied among individuals, but the overall tendency for larger acceleration/jerk discomfort and less tolerance at deceleration than at acceleration remained unchanged for all subjects. Hence in creating the discomfort degree map, we combined all measurement results of all the subjects.

2-3 Simulation-based evaluation of the discomfort degree

We made a module to calculate the discomfort degree caused by vehicle acceleration and jerk using the discomfort degree map. Then, we integrated the module with a vehicle simulation model, and quantitatively evaluated the

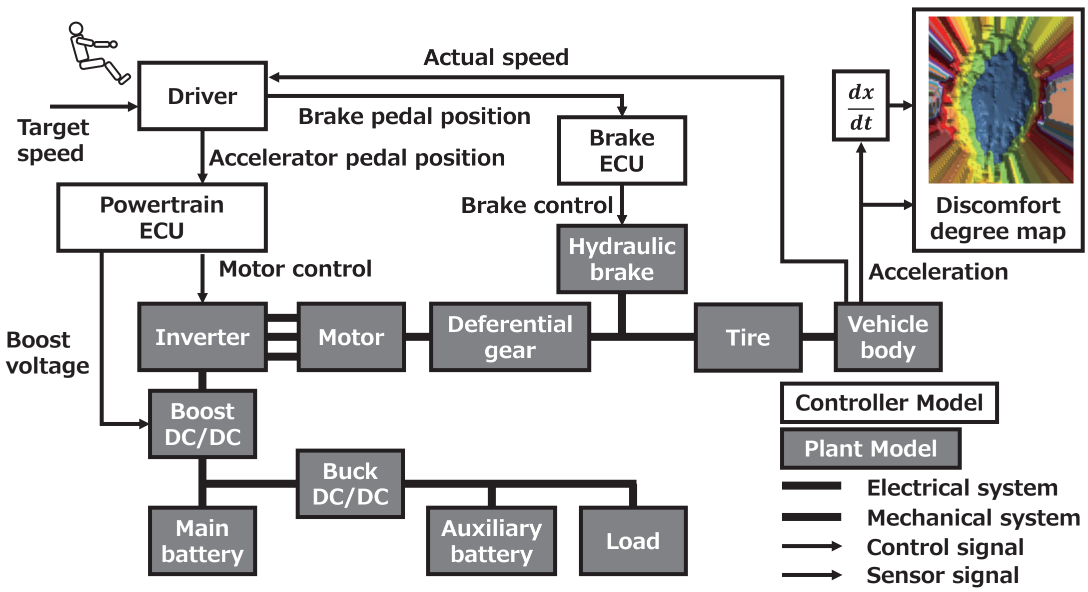

Fig. 3. Overview of the vehicle model

Table 1. Power consumption and discomfort degree on each speed pattern

Speed pattern	Power consumption [km/kWh]	Accumulation of discomfort degree [No Unit]
JC08	10.93	4514.76
FTP	11.28	8255.45
WLTC	9.45	8802.78

discomfort in several different speed patterns.[*5] An overview of the model is shown in Fig. 3, and the simulation result on discomfort degree is shown in Table 1.

3. Verification of Trade-off between Power Consumption and Ride Comfort

Next, we verified the trade-off between power consumption and ride comfort using the model mentioned before.

3-1 Study on ride comfort improvement control

In order to verify the trade-off between power consumption and ride comfort, it is necessary to compare the results of simulations conducted with and without considering ride comfort in the same driving pattern. Since our previous vehicle model had been designed with a focus on the calculation of mode fuel consumption, the powertrain model and the brake model were controlled to generate drive force and brake force according to the input of acceleration and brake signals. Considering this control as the one with no consideration given to ride comfort, we studied ride comfort improvement control and integrated it with the vehicle model.

As mentioned before, the larger acceleration and jerk, the higher discomfort degree. Therefore, it is only necessary to apply a low-pass filter between the accelerator and brake, and restrict the maximum acceleration. However, if we use such simple control, drivers may not avoid collision or other accidents because of the restriction of acceleration. We also needed to consider the nonlinearity in the discomfort degree map. In the case the simple control mentioned earlier was used, the degree of improvement varied depending on the driving conditions because of the nonlinearity. Thus, we studied how to improve ride comfort, and created a controller model according to the result of the study. The control algorithm is shown in Fig. 4.

With the vehicle model, the target torque of the motor is determined by the accelerator or the brake and the actual speed of the vehicle. Since we were able to calculate the acceleration and jerk using the target torque and running resistance, we successfully predicted the discomfort degree from these calculation results and the discomfort degree map. If the predicted discomfort degree was higher than the threshold, a low-pass filter was applied to the target torque in order to make the jerk small. Since this vehicle model was assumed to have an electric powertrain, we adopted a "one pedal control system," which have been used on the electric vehicles of BMW AG. and Nissan Motor Co., Ltd. We decided not to intervene in the brake operation to prevent the interference with the operation and avoid collision accidents.

3-2 Inexperienced driver model

We have created the algorithm for ride comfort improvement control, but the impact of this control was extremely small when the model was speeded up gently. Thus, this driver model was not appropriate for the parametric study of the trade-off between power consumption and ride comfort. Therefore, we created an inexperienced driver model so that the discomfort degree becomes large. Since the vehicle model drove only longitudinally, we defined the "inexperienced driver" as a person who drives with uncomfortable acceleration and deceleration. We studied what the uncomfortable drive is like and what operation causes discomfort, and then created the inexperienced

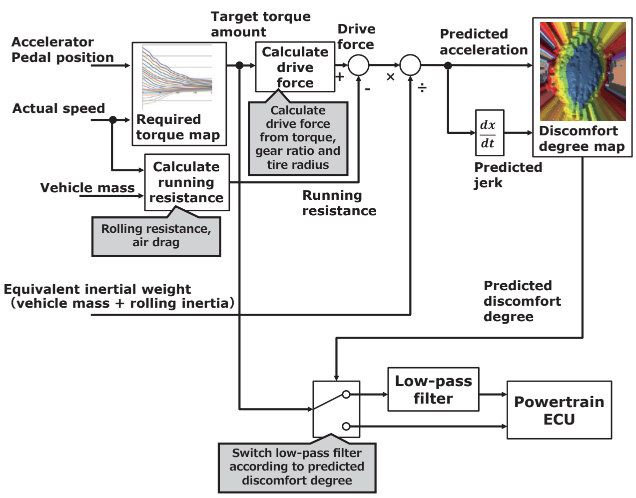

Fig. 4. Algorithm of ride comfort improvement control

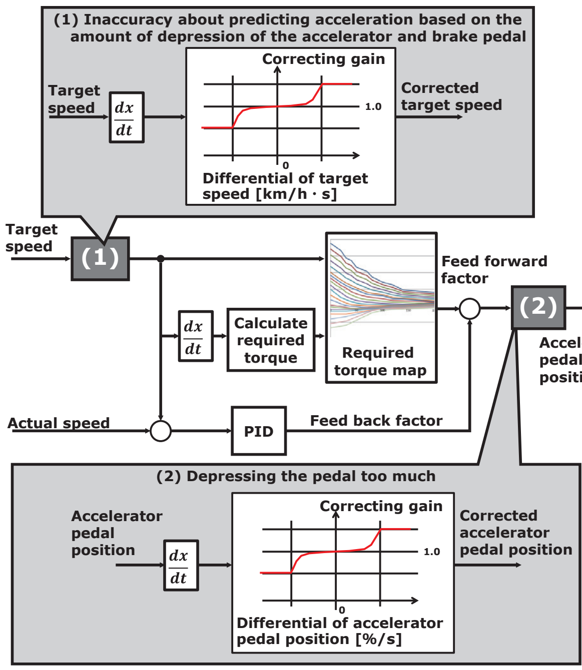

Fig. 5. Inexperienced driver model

driver model according to the result of this study. The inexperienced driver model is shown in Fig. 5. We added two modules that reproduces the factor of uncomfortable driving to the previous driver model. (1) Inaccuracy about predicting acceleration based on the amount of depression of the accelerator and brake pedal, and (2) Depressing the pedal too much.

3-3 Results of power consumption and ride comfort simulation

We calculated power consumption and the discomfort degree in several speed patterns using the vehicle model, ride comfort improvement control, and inexperienced driver model. The results are shown in Table 2. You can see that when the ride comfort improvement control is on, the discomfort degree decreases and the regenerative power also decreases, and these effects are larger with the inexperienced driver model. Power consumption is slightly improved by the introduction of the ride comfort improvement control. We considered that it was due to the suppression of excessive acceleration, thereby reducing power. The waveforms of speed, motor torque, battery current, and discomfort degree with and without the ride comfort improvement control are shown in Fig. 6. You can see that the ride comfort improvement control restricts rapid changes of the motor torque, thereby decreasing the battery current. In this study, we adopted the speed patterns for measuring fuel consumption with only a few times of rapid acceleration and deceleration. Hence, there is only a slightly change in the power consumption. We are planning to verify the trade-off between power consumption and ride comfort with speed patterns that have grater acceleration, considering road slopes and changing vehicle specifications such as motor torque. Additionally, reduction of current is considered to have a large thermal effect and thus it is useful to incorporate heat factors to the vehicle model.

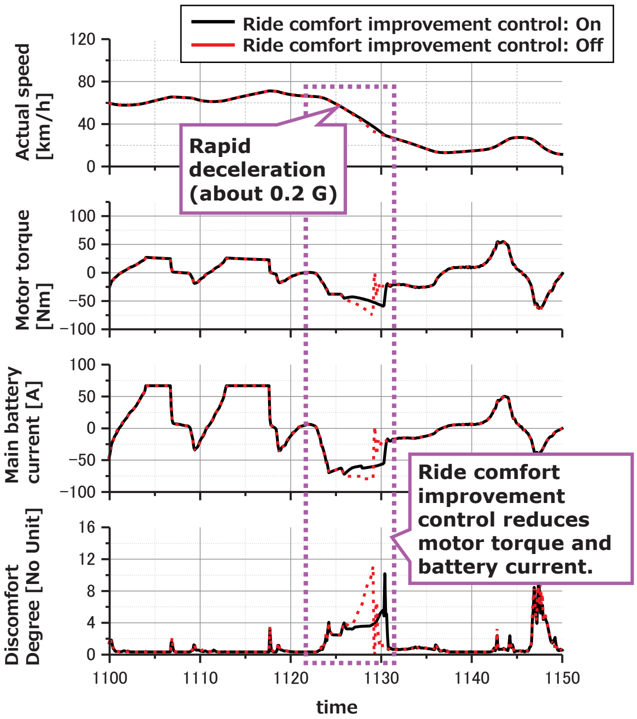

Fig. 6. Comparation of waveforms with and without ride comfort improvement control

4. Conclusion

We studied on the quantitative evaluation of power consumption and ride comfort at the design stage, which can contribute to the development of more efficient vehicles. We created a model to quantify ride comfort. We evaluated the discomfort degree using a real vehicle and mapped the results with acceleration on the x axis and jerk on the y axis. Next, we studied on how to improve ride comfort and integrated the ride comfort improvement control with the vehicle model. Using the vehicle simulation, we verified that the ride comfort improvement control restricts the rapid change of the motor torque thereby suppressing the maximum motor current. With the simulation technique developed in this study, we added “ride comfort” to the evaluation axis of our products. We are

Table 2. Results of power consumption and ride comfort simulation

Speed pattern	Driver model	Ride comfort improvement control	Power consumption [km/kWh]	Accumulation of regenerative power [Wh]	Accumulation of Discomfort degree [No Unit]
JC08	Normal	Off	10.93	381.93	4514.76
		On	10.93	381.87	4393.33
	Inexperienced	Off	10.45	462.35	6537.77
		On	10.45	461.69	6341.11
FTP	Normal	Off	11.28	518.73	8255.45
		On	11.29	518.15	8067.88
	Inexperienced	Off	11.04	569.02	9936.94
		On	11.05	567.66	9487.94
WLTC	Normal	Off	9.45	801.11	8802.78
		On	9.45	800.21	8649.37
	Inexperienced	Off	9.2	962.49	11725.93
		On	9.22	957.11	11116.35

planning to verify the effect of component specifications on power consumption and ride comfort, and propose solutions that surpass our competitors.

This study was conducted in collaboration with AZAPA Co., Ltd. We appreciate their cooperation particularly in experiments using actual vehicles, creation of a simulation model, and verification tests.

Technical Terms

∗1 Regenerative brake: When a vehicle is decelerating, the motor generates power and uses the load of generation as brake force. Normally, a hydraulic brake changes the kinetic energy to thermal energy and disposes of it, but a regenerative brake changes the kinetic energy to electric energy and charges it to a battery, thereby saving power consumption.

∗2 Jerk: Time differentiation of acceleration. According to the equation of motion (F = Ma), a change of acceleration is regarded as a change of force applied. Thus, a large jerk means large force applied rapidly.

∗3 Electric powertrain: A powertrain whose drive force is generated by a motor. Electric powertrains include not only battery electric vehicles but also hybrid vehicles that use electric power generated by the engine to drive the motor.

∗4 low-pass filter: A filter that passes low frequency signals and attenuates high frequency signals. In this study, noise added to the measurement result was considerably high in frequency than that of acceleration to be measured. Thus, the noise could be excluded by an appropriate low-pass filter.

∗5 Speed pattern: A sequence that describes the vehicle speed at any specific time. Inputting the pattern to a driver model as a target speed and the driver model operates the accelerator and brake pedal according to the deviation between the target speed and actual speed. In the fuel consumption measurement, driving a vehicle according to the speed pattern determined every second. JC08, FTP and WLTC are the names of the speed patterns for fuel consumption measurement in Japan, United States, and the world-common respectively.

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