

Development of Road Input Prediction Technology for Setting of Suspension Durability Conditions

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ABSTRACT

Conventionally, durability input conditions for suspension durability performance tests have been set based on wheel input data obtained from actual vehicles. The research discussed in this paper developed a technology for the prediction of the wheel input data necessary for setting durability input conditions without using actual vehicles by means of full vehicle analysis using multi-body simulation. Rough road, curb stone road, winding road, panic braking and pot hole braking were set as the target driving modes, and digital roads were created and an ABS control model was incorporated in order to reproduce the driving modes. In addition, the fact that performing the vehicle set-up assuming the loading of gravity increased accuracy was verified, and it was possible to realize good accuracy in all the target driving modes using a single model. The developed technology makes it possible to set suspension durability conditions without using an actual vehicle.

1. Introduction

Complete vehicle simulations employing multi-body simulation have been utilized in a variety of fields, making it possible to respond rapidly to customer needs through the reduction of development costs. In addition, they have reduced development time⁽¹⁾⁻⁽⁸⁾. Reducing the number of prototypes used during development by means of complete vehicle simulations necessitates a technology able to compute all the items that should be obtained from actual vehicle tests. The suspension is one of the parts subject to durability evaluation of the vehicle body. The flow of evaluation of suspension durability is as follows. Using a prototype vehicle, the loads generated at the centers of the wheels are measured, and these figures are used in calculating the load allocated to each part. Next, with these allocated loads as input loads, unit component evaluations and evaluations of components in combination are conducted using bench test devices (Fig. 1). As this

indicates, a vehicle test is necessary only to obtain the load input to the centers of the wheels. If a simulation could be substituted for this measurement of input via a vehicle test, it would be possible to realize a development flow that did not use actual vehicles. This paper discusses the reproduction of driving modes, the adjustment of vehicle parameters and the creation of tools for the realization of increased accuracy, and the verification of accuracy towards the creation of a complete vehicle simulation technology using multi-body simulation and the realization of results of sufficient accuracy to be substituted for vehicle tests.

2. Overview of Complete Vehicle Simulation

A full vehicle model employing multi-body simulation was created in order to determine the inputs generated when vehicles travel on roads (Fig. 2).

A model of the 2008 FIT, a CVT vehicle with a 1.5-L engine, was formulated for study. For rough roads and curb stone roads, methods developed for use in previous studies were employed as references in the development of the model⁽¹⁾⁻⁽³⁾. The body, suspension arms, knuckles, hubs and other parts were modeled as rigid parts, while the torsion beams were modeled as flexible parts. A wheel force transducer model was created at the wheel center for evaluation of the input load.

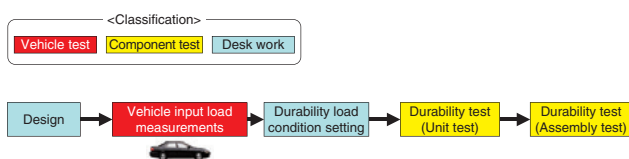


Fig. 1 Suspension development flow for durability

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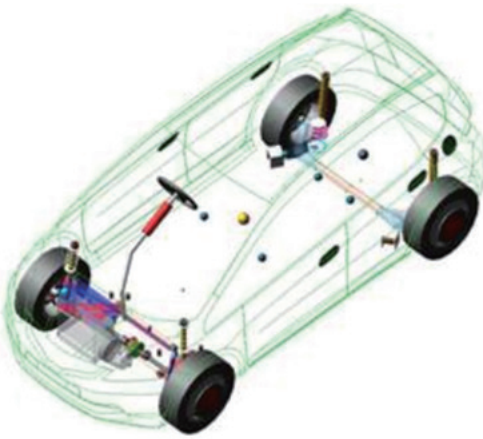


Fig. 2 Full vehicle simulation model

3. Creation of Model Environments for Reproduction of Driving

Loads from the road surface are input to the suspension in a variety of directions depending on the driving conditions. Driving modes have therefore been established for various directions of input to help ensure durability. In order to determine conditions for durability using a simulation, it is necessary to reproduce driving in all of these modes. Therefore, the organization of the necessary driving mode, digitalized the road surface in response to each driving mode, and select the variety of tire model and coupling technology between the multi-body simulation with a MATLAB/Simulink model for reproducing brake ABS behavior were applied in this project

3.1. Extraction of Driving Modes

Five driving modes are necessary for the determination of conditions for suspension durability. These are: winding road, panic braking, pot hole braking, curb stone road, and rough road. Figure 3 shows the driving modes and the corresponding target load directions.

3.2. Creation of Digital Road Surfaces

Three standard methods of creating a digital road surface are available.

Method (A): Shapes are expressed as mathematical formulas. This method is used for two-dimensional road surfaces or 2.5-dimensional road surfaces that reproduce the road surface shape only in the direction of the vehicle movement.

Method (B): Shapes are reproduced using triangular patches. This method is used for road surfaces for which detailed three-dimensional reproduction is necessary. Because ASCII format is used for descriptions and the road shapes are complex, computation costs tend to be high for this method (Fig. 4).

Method (C): Using a grid shape as the basis, three-dimensional shapes are reproduced by means of data in the direction of height for each point of intersection. This

method is used for road surfaces for which the reproduction of complex three-dimensional shapes is necessary. Increases in computational cost can be minimized by using binary data and computing three-dimensional road surfaces after simplifying the expression of the shape by means of the grid concept⁽⁹⁾ (Fig. 5).

Based on considerations of computation cost and the necessity of reproducing the road surfaces, the research discussed here selected the following model creation processes for the generation of digital road surfaces (Fig. 6).

Method (A) was selected for the reproduction of panic braking, for which a flat plane can be computed. Method (B) was selected for curb stone road, pot hole braking, and winding road modes, which necessitate detailed three-dimensional shapes but do not feature continuous concavities and convexities. For rough roads on which complex concavities and convexities occur continuously and it is necessary to reproduce shapes with a

Driving mode	Target load direction
Winding	Mx
Panic braking	Fx, My
Pot hole braking	Fx
Curb stone	Fx, Fz
Rough road	Fx, Fz

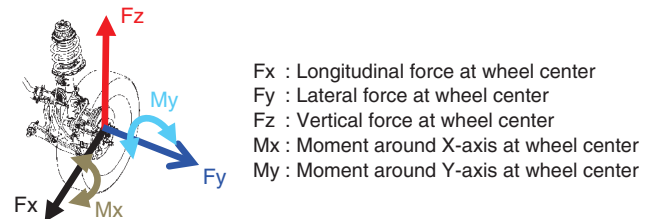


Fig. 3 Driving mode for each load direction

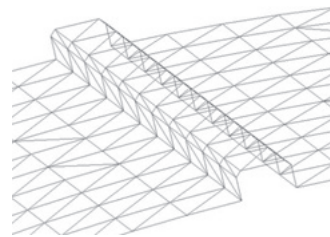


Fig. 4 Image of format (B)

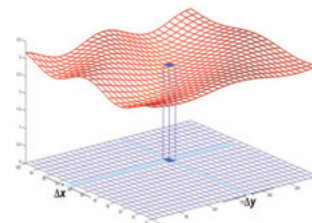


Fig. 5 Image of format (C)

high level of accuracy, the marked increase in computation cost occasioned by the use of method (B) represented an impediment to the performance of the computations, and method (C), which is slightly inferior to method (B) in terms of reproduction of shapes but offers a sufficient level of reproduction for the evaluation of durability in addition to realistic computation costs, was therefore selected.

For curb stone and rough roads, road surface measurement data obtained in previous studies was used as the basic data for the generation of road surface models. In the case of pot hole braking, drawing data was employed, while for winding road, road surface measurements were conducted and the data was digitalized.

3.3. Selection of Tire Models

From among the tire models available for multi-body simulation, the present research selected FTire⁽⁹⁾ and Magic Formula tires from considerations of compatibility with a software in multi-body simulation and cost of introduction. These two types of tire model were employed in response to the characteristics of the specific driving mode in use. Magic Formula reproduces lateral force, longitudinal force and other forces generated on the tire as tire models using mathematical formulas, making it possible to control computation costs. It is generally employed to conduct studies in vehicle dynamics analyses. FTire models reproduce the steel belts of the tires as a mesh, making it possible to reproduce the tires' envelope characteristics. Because FTire models are able to reproduce the behavior of the tires around their points of contact with the road surface in detail, computation cost increases. On the other hand, the models are also able to reproduce the envelope characteristic, the tire's property of wrapping around small projections, with a high degree of accuracy. FTire models are used in a range of applications, from computations for the area of strength and durability, as in the present research, to calculations for the area of passenger comfort.

In selecting tire models, the research focused on the

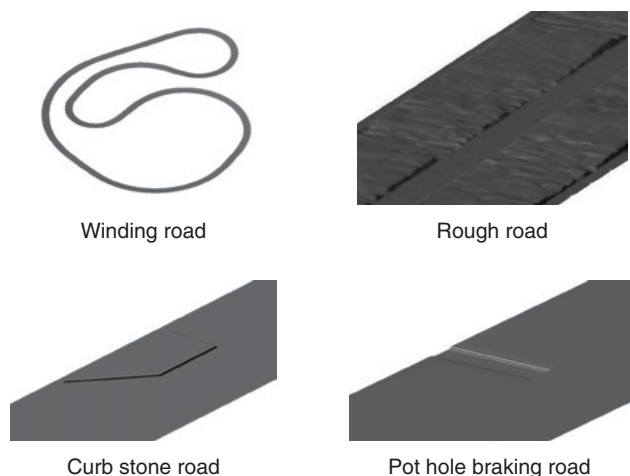


Fig. 6 Road shape for each driving mode

Table 1 Varieties of tire model

Driving mode	Tire model	
	FTire	Magic Formula
Winding		✓
Panic braking		✓
Pothole braking	✓	
Curb stone	✓	
Rough road	✓	

necessity for accuracy in envelope characteristics in each driving mode. In the case of winding road and panic braking, while it was necessary to consider height differences on the road and the gradient in the lateral direction, the mode featured driving on a comparatively flat road, and it was therefore considered that the necessity for accuracy in reproducing the tires' envelope characteristics was low. A Magic Formula tire model was therefore selected. By contrast, pot hole braking, curb stone road and rough road are modes in which the tires pass over projections of various sizes, and the reaction force generated by the tires would differ depending on the shape of the projection and the state of the tire. Given this, it was considered that it was necessary to reproduce envelope characteristics accurately, and an FTire model was therefore selected (Table 1).

3.4. Application of Technology for Coupled Analysis of Multi-body Simulation and Control

For the panic braking and pot hole braking modes, it is important to reproduce ABS characteristics. The model was therefore coupled with a MATLAB/Simulink model that modeled the ABS characteristics. Figure 7 provides an overview of the model.

The coupled simulations between multi-body simulation and control were conducted using MATLAB/Simulink. The Simulink model was composed of a vehicle model block created by changing the format of a multi-body simulation model to S-function format, a controller block that applied ON/OFF control to the brake pistons as ABS control, and a hydraulic unit block that controlled hydraulic pressure. Vehicle behavior was obtained from the multi-body simulation model for use in computations in the respective blocks, and ABS behavior was reproduced by calculating the brake piston pressure generated for each wheel.

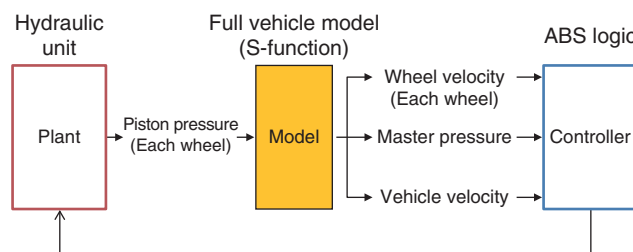


Fig. 7 Co-simulation flow in MATLAB/Simulink

4. Adjustment of Model Parameters

4.1. Verification of Accuracy by means of Constant-radius Cornering

Previous papers have treated the verification of accuracy for rough roads and curb stone roads⁽¹⁾⁻⁽³⁾, and the present research therefore restricted its focus to winding roads, panic braking and pot hole braking, and narrowed down the necessary items for adjustment of parameters by means of constant-radius cornering (Fig. 8).

Figure 9 shows a comparison of results for the change in the load on the outer front wheel during cornering.

Based on the simplicity of the constant-radius cornering driving mode, the complexity of the target driving mode, and the final target for accuracy, a target accuracy of within 5% was set for efforts to increase accuracy.

4.2. Contribution Analysis for Increased Accuracy

A contribution analysis was conducted in order to narrow down the parameters for enhancement of the model towards the realization of increased accuracy. The analysis was conducted for the parameters shown below. Figure 10 shows the results of the analysis.

- (1) Mass, height of center of gravity, and moment of inertia of complete vehicle
- (2) Initial toe and initial camber
- (3) Damper damping, spring stiffness, bump stop stiffness, stabilizer stiffness
- (4) Bush stiffness and damping

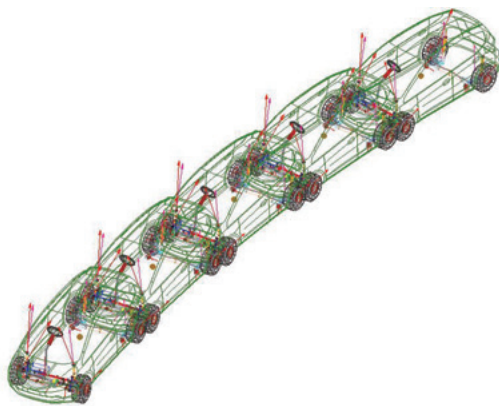


Fig. 8 Constant radius cornering

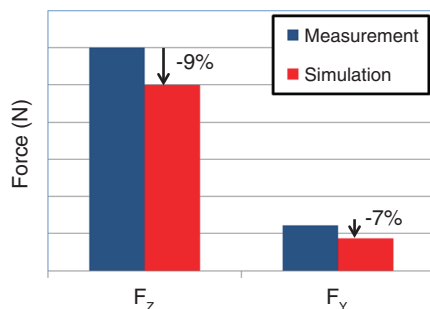


Fig. 9 Comparison of front wheel load at wheel center

The results showed a high level of contribution for the complete vehicle mass, initial camber, height of center of gravity and initial toe. These results indicated that the parameters defining the initial state of the vehicle displayed a high level of contribution. The next highest contribution was displayed by parts stiffness items, such as the stiffness of the rear bump stop and the front stabilizer. In the present research, efforts were made to minimize error, for example by using the measurement data for rear bump stop stiffness and, in the case of front stabilizer stiffness, employing parts of the same specifications as had been used in analyses in an actual vehicle. For the reasons discussed above, the research focused on the reproduction of the initial state of the vehicle in attempting to increase accuracy.

4.3. Verification of Reproduction of Initial Vehicle State

Figure 11 shows the computation process for conducting driving computations from the stage of construction of a full vehicle model.

- Step 1: Vehicle parameters for the state of the vehicle at the stage of creation of the model are adjusted to match the vehicle characteristics that are the subject of computations.
- Step 2: Static equilibrium calculations are conducted with 1 g of gravity ($1\text{ g} = 9.8\text{ m/s}^2$) imparted to the vehicle model. This state is defined as the state in which the vehicle is stabilized by 1 g of gravity ("1 g condition").
- Step 3: The desired driving mode is calculated using the vehicle state described in Step 2.

Normally, vehicle parameters for the reproduction of the initial vehicle state are adjusted in Step 1. However, given

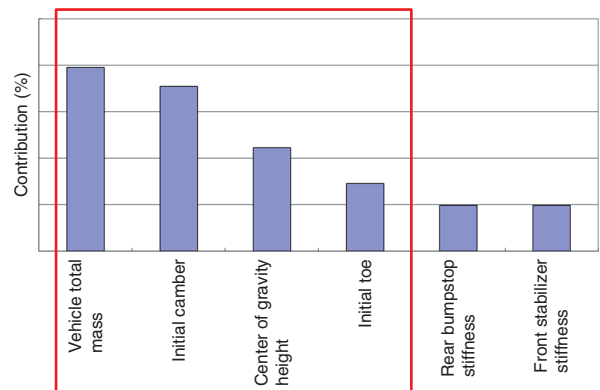


Fig. 10 Results for contribution of parameters

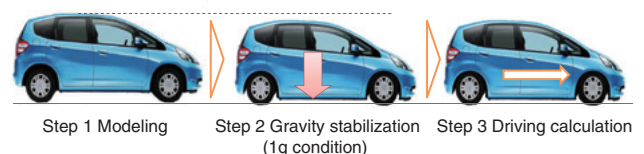


Fig. 11 Process for driving calculation

Table 2 Variation in set parameters due to 1 g load

Set parameter		Modeling (Step 1)	1g condition (Step 2)	Error
Center of gravity height (mm)		494	449	-45
Initial toe (deg)	Front	0.00	0.01	+0.01
	Rear	0.10	0.34	+0.24
Initial camber (deg)	Front	0.00	-0.56	-0.56
	Rear	-1.00	-1.39	-0.39

that gravity of 1 g is acting on an actual vehicle at all times, the state in Step 2 (1 g condition) can be considered to be the initial state to which the model should be matched. The amount of change in the vehicle parameters from Step 1 to Step 2, with a load of 1 g of gravity applied, was therefore studied. The results are shown in Table 2.

Based on the results shown in Fig. 10, the height of the center of gravity, the initial camber, and the initial toe were selected as the vehicle parameters to be focused on. Vehicle mass, which had displayed the highest degree of contribution, was excluded as an item because it did not change under gravity of 1 g.

The results obtained in this study confirmed that the vehicle parameters changed from the target values for vehicle characteristics set for the initial state in the model creation process (Step 1) under a load of 1 g gravity. The height of the center of gravity and the initial camber displayed a particularly significant degree of change, and these were therefore items to be enhanced in the quest for increased accuracy in the analysis. This was considered to result from the fact that the model had been created with reference to drawing data, but the vehicle state used in durability evaluations differs from the vehicle state assumed in this data.

4.4. Enhancement of Method of Reproduction of Vehicle Characteristics

It was considered that in order to increase the accuracy of driving analysis, it would be necessary to adjust vehicle parameters under the 1 g condition rather than at the stage of model creation. However, because the 1 g condition was the result of static equilibrium calculations, it was not possible to directly adjust model parameters in relation to it. In the case of the height of the center of gravity, which displayed a significant difference from its initial value under the 1 g condition, the initial value was re-set with consideration of the degree of change under the 1 g condition, as shown in Fig. 12.

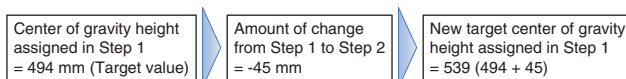


Fig. 12 Flow of adjustment of target value

Figure 13 shows a comparison of loads with a model in which the parameters had been adjusted based on the concept described above.

The results show an enhancement of load transition, with a difference in load of 5% for F_z and 2% for F_y , and a consequent increase in the accuracy of lateral force, realizing reproduction that meets accuracy targets.

4.5. Development of Tool for Automation of Process

Results had indicated that adjustment of vehicle characteristics under the 1 g condition was essential for the realization of increased accuracy.

Attempting to increase the accuracy of analysis as much as possible, the present research aimed to set all of the vehicle set-up parameters that it is necessary to manage in actual vehicle tests under the 1 g condition. Vehicle height, bump stop clearance, initial toe, initial camber, height of the center of gravity and moment of inertia around the center of gravity were selected as the vehicle parameters. Because there is mutual interference between vehicle height, bump stop clearance and height of the center of gravity, it was necessary to conduct iterative calculations similar to convergence calculations for these parameters. This made it impossible to use the simple method discussed in Section 4.4, which significantly increased the person-hours for procedures during the adjustment of the model, making the method unsuitable for use in the automotive development process.

Given this, a tool to make it possible to automate the vehicle parameter adjustment process while maintaining the 1 g condition was developed in order to save time. The resulting tool reduced the person-hours involved in adjustment of parameters and made it possible to apply the method in the automotive development process.

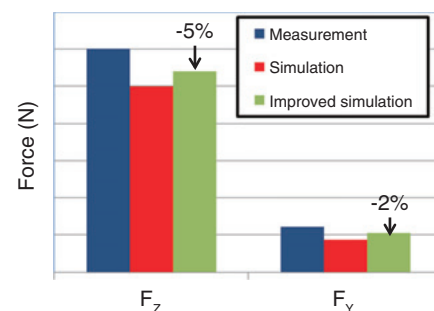


Fig. 13 Reevaluation of front wheel load at wheel center

5. Verification of Accuracy in Target Driving Modes

Accuracy in the target driving modes was verified using the models in which accuracy had been enhanced. The results are shown in Figs. 14 to 20.

(a) Winding

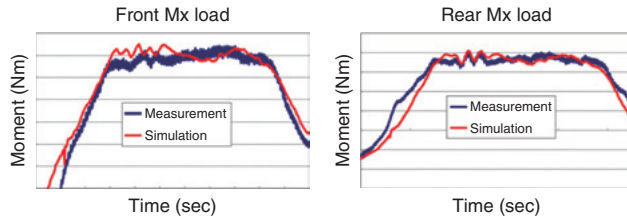


Fig. 14 Moment around X-axis at front and rear wheel center

(b) Panic braking (ABS control)

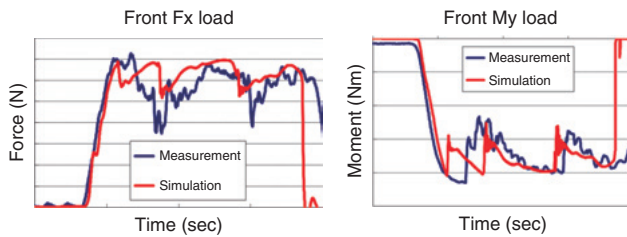


Fig. 15 Longitudinal force and moment around Y-axis at front wheel center

(c) Pot hole braking (ABS control)

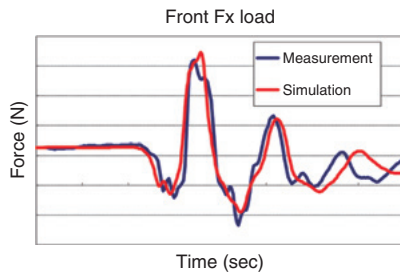


Fig. 16 Longitudinal force at front wheel center

(d) Curb stone

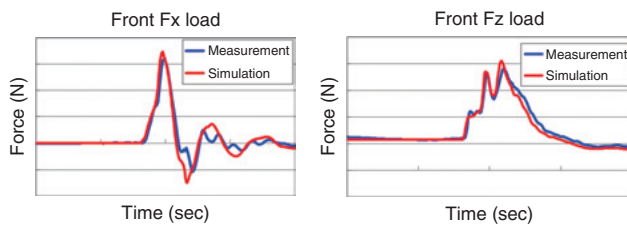


Fig. 17 Longitudinal and vertical force at front wheel center

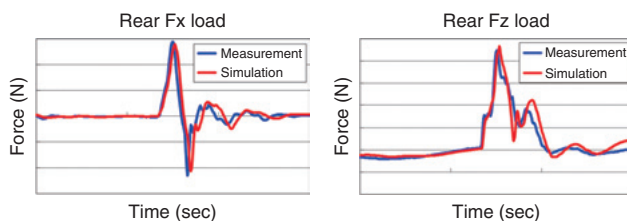


Fig. 18 Longitudinal and vertical force at rear wheel center

(e) Rough road

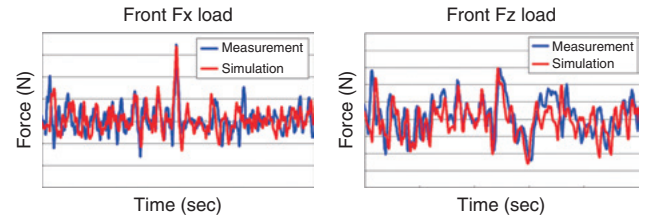


Fig. 19 Longitudinal and vertical force at front wheel center

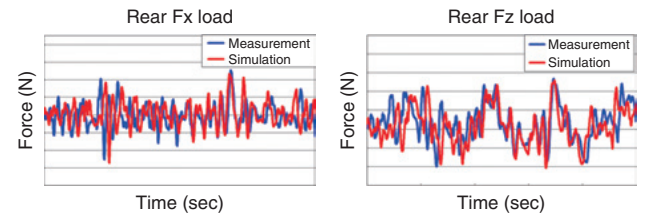


Fig. 20 Longitudinal and vertical force at rear wheel center

A good correlation with vehicle test results was achieved for target loads for all target driving modes. This was considered to demonstrate that the models achieved sufficient accuracy for use as a substitute for vehicle tests.

6. Conclusion

The following technologies were developed as a substitute for the measurement of inputs in vehicle tests in order to determine suspension durability conditions, and were refined for application in the automotive development process.

- (1) Digital roads were created and tire models were selected in order to reproduce all the driving modes necessary for vehicle input measurement tests via multi-body simulation using a single model.
- (2) The importance and effectiveness of employing vehicle parameters incorporating the 1 g condition in increasing accuracy was verified, and a tool was developed in order to reduce adjustment time.
- (3) The accuracy of the method was tested, and it was verified as offering sufficient accuracy for use as a substitute for vehicle tests.

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