

Development of Chassis Performance Design Technologies for MBD of Mass-production Vehicles

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ABSTRACT

Technologies have been developed that enable practical application of MBD in function design and performance design stages using the V-model, in order to realize efficient development of mass-production vehicles incorporating complex systems. These technologies, all essential for the application of MBD in mass-production vehicle development, can be broadly divided into three categories: a technology that reduces the time necessary for the formulation of simulation models; a technology that reduces the time necessary for the definition of simulation conditions; and a technology that reduces the time necessary for the sharing of simulation results. These technologies have reduced the simulation output time for MBD in function design and performance design stages to approximately 1/50th of the previously required time. As a result, it has become possible to apply MBD in function design and performance design during the development of mass-production vehicles.

1. Introduction

With the ongoing development of today's mobile society, the automotive market is no longer concentrated in developed nations and is expanding in emerging nations, resulting in considerable automotive diversification. As Fig. 1 shows, an increased focus on environmental issues is propelling diversification of engines, motors, and hybrid powertrains. Changes in lifestyles are diversifying categories, resulting in the development of sedans, minivans, SUV, and other vehicle types in order to reflect customers' needs. With increasing safety requirements, a variety of driving support systems such as SH-AWD and Active Yaw Control are being fitted in vehicles, and devices and electronic systems are diversifying. As a result, automotive systems have rapidly become more complex in recent years⁽¹⁾⁻⁽³⁾.

When developing complex systems, prior to entering into consideration of fine details such as the shapes and characteristics of the components comprising the system, designers examine whether or not the system adequately fulfills its intended functions. In doing so, an effective method is to consider the system mechanisms based on the components making up the general framework, and to study the functions of the system overall^{(4), (5)}. A development process that moves on to detailed study of the constituent components when directions for potential specifications have been obtained at this stage enables efficient creation

of complex systems⁽⁶⁾. This type of process can be generally expressed as the V-model shown in Fig. 2⁽⁷⁾. In this model, the design stages running in sequence from the upstream of the design process are called conceptual design; function design and performance design; and structural design and parts design.

The function design and performance design stages positioned between the upstream conceptual design and the downstream structural design and parts design stages

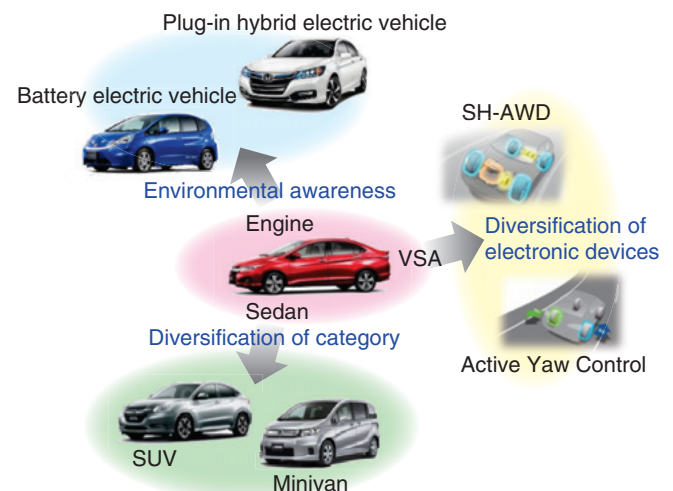


Fig. 1 Automotive diversification

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are important to the efficient and optimal development of complex systems. Model-based development (MBD) methods, involving verification in actual vehicles only after outlooks for potential specifications have been obtained through consideration of specifications at the desk using simulation models, are available for studies at the function design and performance design stages⁽⁸⁾.⁽⁹⁾ An alternative development approach, in which no simulations are conducted and studies commence with the creation of prototypes, and specifications are determined experimentally through repeated trial and error until targets are satisfied, will be termed “model-free development” (MFD) in this paper. Figure 3 expresses each of these development processes as flow charts⁽¹⁰⁾.

The introduction of MBD necessitates the formulation of simulation models (simply termed “models” below) of the vehicle that is the subject of the development. The formulation of the initial model takes time, but when this model has been completed, it is possible to proceed with the study of specifications at the desk, doing away with the necessity of repeating the process of trial and error numerous times using a real vehicle. In addition, because the system mechanisms are clearly incorporated in the model, the effects of solutions employed to realize target

performance are also clear. By contrast, because MFD commences the process of study of the specifications with verification tests in actual vehicles, without using models, the process of trial and error is repeated with the system mechanisms still uncertain, making it challenging to understand the effects of the solutions employed to realize target performance. When engaged in the development of comparatively simple systems, MFD may allow the goal to be reached within a shorter period, but as the complexity of the systems increases, the level of difficulty involved in searching for solutions to realize target performance also increases, and there are cases in which it may not be possible to determine an outlook towards the realization of the targets when MFD is employed.

While the application of MBD using the V-model to the development of vehicles incorporating complex systems is essential, it will be necessary to reduce the time required for function design and performance design in order to apply MBD in the development of mass-production vehicles. To date, there has been no consideration of concrete methods in relation to the time necessary for computational studies using simulations and the degree of reduction in the necessary time for the application of MBD in development for mass production. This paper will discuss research conducted to clarify the time restrictions on function design and performance design, and develop technologies that would make the application of MBD practical, in order to enable application of MBD using the V-model to chassis development for all mass-production models in development.

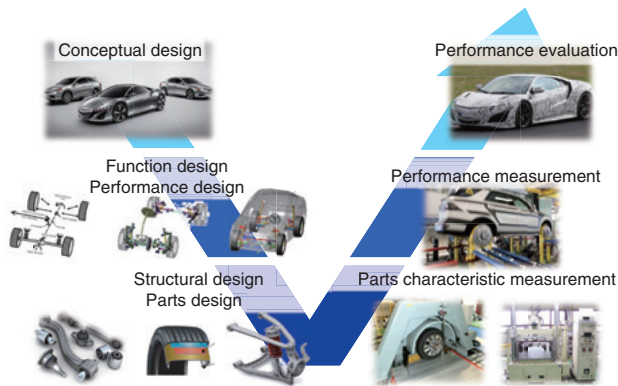


Fig. 2 V-Model for chassis development

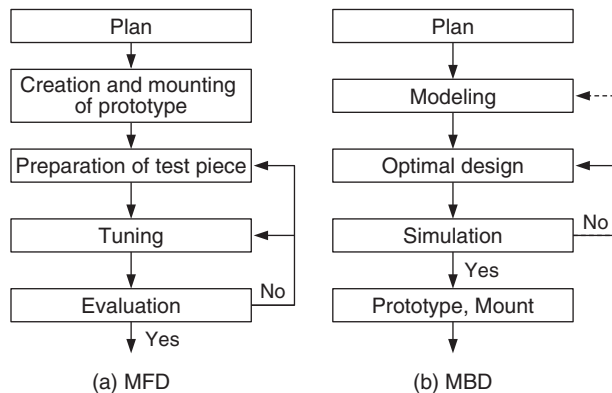


Fig. 3 Concept of MFD and MBD

2. Function Design and Performance Design

1D simulations⁽⁸⁾ play an important role in implementing MBD in automotive function design and performance design. In 1D simulations, the characteristics of the constituent components of the vehicle are represented as blocks, and the reciprocal effects of components on each other are expressed as connections shown by arrows. MATLAB/Simulink is a standard 1D simulation tool. The main focus in terms of function design when formulating models is considering how the vehicle systems should be understood and what is the structural makeup of the mechanisms in the model. When the preliminary model that is initially formulated based on function design is completed, designers determine and consider the optimum combination of component characteristics. This is the main focus in terms of performance design. Even if the details of the dimensions and characteristics of the actual individual components have not been decided, if the overall characteristics of the components have been defined, it is possible to proceed with computation-based studies using 1D simulations⁽¹¹⁾.

When studying whether a specific configuration offers a potential outlook for the achievement of the target functions and performance using 1D simulations, if no viable

direction can be determined at a specific time, then it is necessary to change the configuration of the system. There is a mutually complementary relationship between function design and performance design, and both are essential to the implementation of MBD. Figure 4 diagrammatically illustrates function design and performance design concepts in relation to the roll motion of a vehicle. The top image in Fig. 4 shows a study of an adequate model for the computation of roll motion. The middle and bottom images show studies of the characteristics of the components in this model for the computation of roll motion. Here, the middle image corresponds to function design and the bottom image to performance design. Broadly speaking, function design considers the composition of the system, and performance design considers the combination of component characteristics^{(12), (13)}.

When the component characteristics that will be reflected in the final design drawings are determined, the number of items reaches several hundred. Figure 5 shows part of a table of these items. Here, this will be termed a performance design item list. The vertical columns show items for which system target values exist (simulation output), and the horizontal rows show items representing characteristics of the individual components making up the system (items for parameter studies). Performance design using 1D simulations seeks the optimum solution

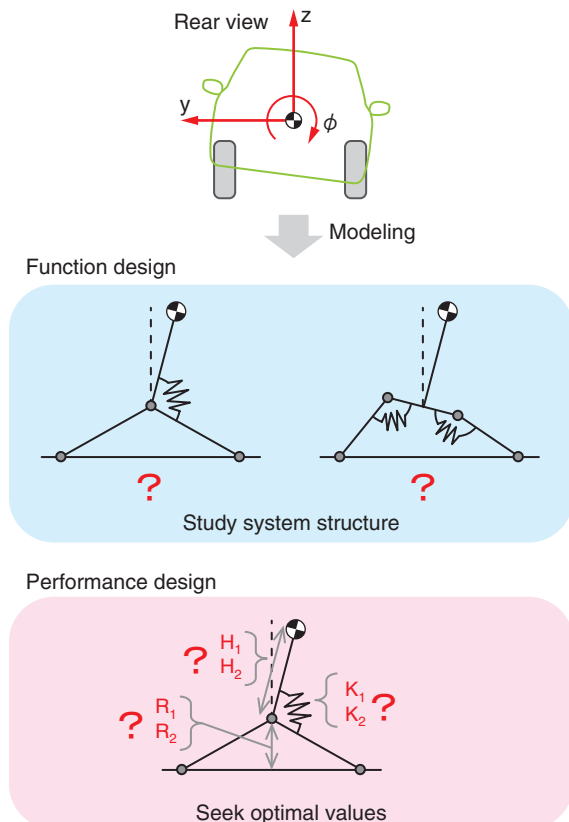


Fig. 4 Function design and performance

from the combination of these several hundred component characteristics.

The time necessary for function design and performance design is the time from the formulation of an adequate model to the sharing of the results of calculation studies with structural designers. In concrete terms, this includes the time necessary for searching for the optimum combination of component characteristics, deciding all of the values to be incorporated in the performance design item list, and outputting a report of calculation results, up to the sharing of data in report briefings and other meetings.

	車両										タイヤ									
	車両諸元(寸法)					車両諸元(重量)					操安関連					乗				
	全長	全幅	ホイールベース	トレッド	車高(含定機込込)	エンジン出力	トランスミッション位置	ピッチ慣性モーメント	ロール慣性モーメント	ヨー慣性モーメント	定軸下重量	ばね下重量	回転部相当重量	S/R	荷重-C/P特性	荷重-キャンバースラス特性	スリップ角-C/F特性	キャンバースラス特性	スリップ角-制動力特性	タイヤねじりばね
内輪タイヤ中心最小回転半径																				
車体最外側最小回転半径																				
ヨーレート定常ゲイン																				
ヨーレートピークゲイン																				
ヨーレート共振周波数																				
ヨーレート減衰レベル																				
ヨーレート位相遅れ@0.5Hz																				
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Fig. 5 Performance design item list

3. Technological Issues

In order to determine specifications in mass-production vehicle developments, various prototypes are formulated for a specific range of characteristics, and these prototypes are combined in a process of trial and error, with the optimum specifications determined experimentally. Based on a survey of the time expended on the process of trial and error in MFD conducted between 2010 and 2011, it was estimated that the average time per trial run until a judgment was made was around six hours.

Generating results from simulation computations in a shorter time than the time per trial run in MFD would be an effective means of realizing the application of MBD to the development of mass-production vehicles. This would mean producing results from the computations conducted in MBD in less than six hours.

However, as of 2010, function design and performance design for certain specific mass-production vehicles took

a combined total of approximately 300 hours. In order to practically apply function design and performance design using MBD to mass-production vehicles, it would therefore be necessary to reduce the time required to 1/50th of the normal amount. Figure 6 compares the time taken by repeated trial and error in MFD with that until computation results are obtained in MBD as the height of bar graphs.

What should be borne in mind here is that the process of trial and error in MFD is in fact not concluded with one trial; the process is repeated numerous times, and the more complex the system in development is, the greater the increase in the number of trials.

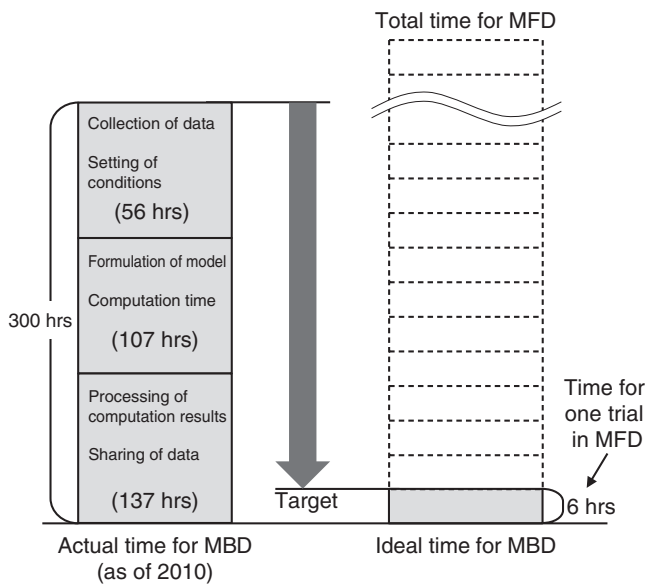


Fig. 6 Target for time reduction

4. Approaches to realizing Practical Application of MBD

4.1. Reducing Time Required for Function Design

The major issue in transitioning from MFD to MBD is reducing the time required for both function design and performance design. The discussion here will first consider the approach to reducing the time required for function design.

When studying a diverse range of characteristic values while seeking the optimum specifications to realize the target values for a complex system, the approach is to begin by studying the most important characteristic values for the system using a simplified model, steadily increasing the detail of the model in order to gradually proceed with the study of the range of characteristic values. Simulations are conducted in a number of stages in this process, but there has been no clear template for the separation of the process into stages, and conventionally individual models have been

formulated for each model in development, with component characteristics individually determined as well. Because of this, every study requires time for the formulation of models. If it were possible to determine the necessary details for studies in each stage and define the model to be used at each stage in advance, it would basically no longer be necessary to expend the time currently employed in formulating models. The research under discussion divided this process into three stages, and established standard models that would allow proceeding with function design for almost any vehicle model in development.

For the first stage, a model was defined that would realize the necessary accuracy in a short period of time. The simulation in this first stage will be termed Level 1 here. As the graph in Fig. 7 shows, the items that can be treated in the simulation increase as the model becomes more detailed, but the labor involved in seeking solutions that realize the target performance also increases. The broken arrow in Fig. 7 shows Level 1. While calculation proceeds in a short period of time, a relatively large number of items can be treated in this model. Because the Level 1 model is a simple block diagram of the type shown in Fig. 8, it can also be easily expressed as a numerical formula. Calculations can therefore be conducted using spreadsheet software such as Microsoft Excel, making this model ideal for rapidly proceeding with parameter studies⁽¹⁴⁾⁻⁽¹⁶⁾.

For the second stage, a model was defined incorporating all of the minimum number of necessary elements for the calculation of all the items in the performance design item list. Here, this simulation will be termed Level 2. The Level 2 model is a block diagram of the type shown in Fig. 9. Because it is more challenging to express this model

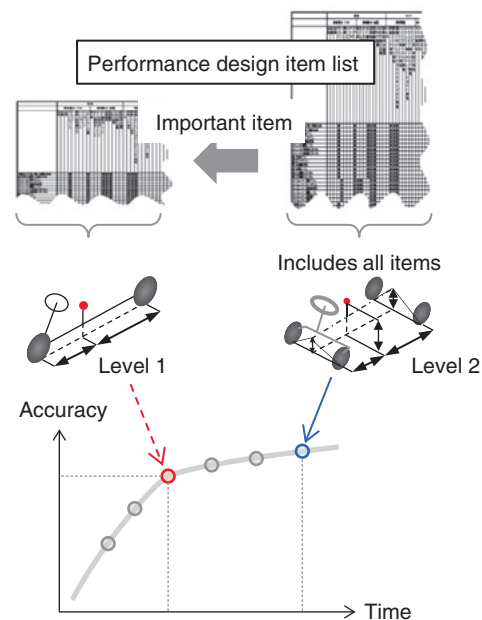


Fig. 7 Relationship between detail of model and output speed

exclusively in mathematical formulas, it is not suited to studies using tools like spreadsheet software. The use of specialized 1D simulation software such as MATLAB/Simulink would be more effective⁽¹⁷⁾.

The model in the third stage is a multibody dynamics analysis model that models all of the components making up the chassis. This type of model is generally called a full vehicle simulation. Here, this simulation will be termed Level 3. Figure 10 shows an image of an animation of a simulation model conducted using ADAMS. The Level 3

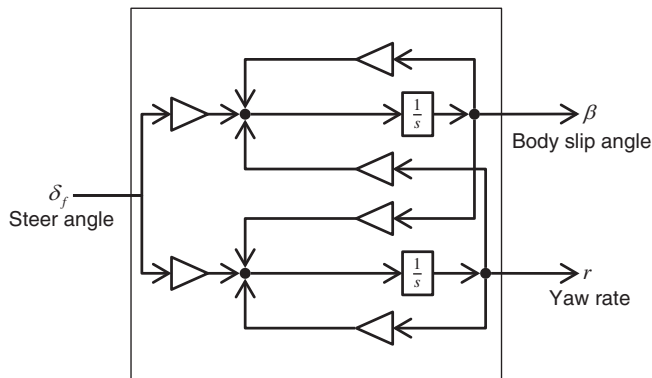


Fig. 8 Model for Level 1

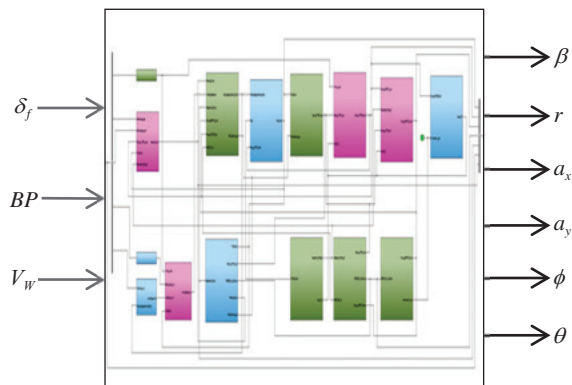


Fig. 9 Model for Level 2

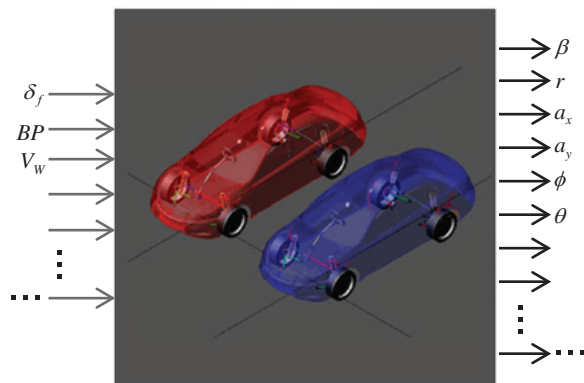


Fig. 10 Model for Level 3

simulation is a 3D simulation rather than a 1D simulation⁽¹⁸⁾.

As of 2016, if designers have models from Level 1 to Level 3, it is possible to study dynamic performance for almost all vehicle models in development. It may be considered that it would be possible to apply MBD to the development of mass-production vehicles using Level 3 (the level at which the most detailed computations can be conducted) alone, but in fact the use of Level 3 only would not allow the achievement of the intended goals. This is because conducting performance design at Level 3 without Levels 1 and 2 would take more time; simply setting the computation conditions for Level 3 would require more time than the target time⁽¹⁹⁾.

4.2. Reducing Time Required for Performance Design

The approach to reducing the time necessary for performance design will next be discussed. In order to reduce the time expended on performance design, the research focused on the time from the setting of specific conditions to the sharing of simulation results with relevant parties, known as output time. In addition to the formulation of the computation model, time is expended in MBD chassis performance design on collecting data and setting computation conditions, and on processing computation results and sharing reports. Figure 11 shows a breakdown of output time.

Even if computation time were to be reduced, the time required for setting computation conditions and defining input items would weaken the effect in reducing output time. In addition, when results are output, if the compilation of those results into reports and the sharing of those reports with other parties takes time, the effect is the same. It was apparent that a great deal of time other than computation time was expended in the entire process, and that this was a factor making the reduction of the time necessary for performance design challenging. The time required for the development of a specific model was measured, and the results are presented as a graph in Fig. 6. A survey of this graph shows that even if the time necessary for the formulation of the model were to be reduced, it would not go far towards the realization of the target reduction.

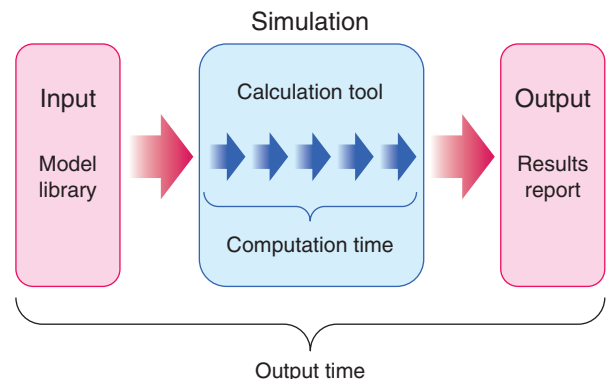


Fig. 11 Computation time and output time

Performance design can be broadly divided into a first half and a second half. The reduction of the time expended in the first half of the process will initially be discussed. The previous section discussed the definition of three models in order to reduce the time expended on function design; it was possible to unambiguously determine the input and output of the simulations using these models. Because input and output would always be the same if the same models were always used, it would be a simple matter to automate the processes related to input and output if the same data format were employed. It would be possible to program the simulation tool in advance to help ensure that input and output data matched the format of the performance design item list, and that Level 1 and Level 2 data were formulated. The creation of a model library is an example of this type of process. Here, “model library” is a general term for a database that stores simulation calculation conditions and a conversion system that enables the simulation tool to directly import the data. The development of a technology that automatically selects simulation conditions from the model library and automatically inputs them to the simulation tool reduced the time necessary for collecting data and setting calculation conditions, which had previously been performed by human operators. Figure 12 compares the time required for input procedures in 2010 and 2014 as bar graphs. These graphs show that the developed technology has reduced the time necessary for the first half of the performance design process to 1/30th of that previously required.

A further issue in reducing the time necessary for performance design was the reduction of the time needed for the compilation of the simulation results into reports and the sharing of the data, corresponding to the second half of the procedure. Conventionally, results have been obtained from computations using a different model each time. These results have then been compiled into a variety of materials and individual reports have been made in order to share data.

If it were possible to output computation results from the Level 1 and Level 2 models in accordance with the items on the performance design item list, it would be a simple matter to automatically formulate the data as graphs or in another desired format. This would reduce the time required for the compilation of reports. The authors defined these automatically formulated reports as part of the performance specifications, and developed an environment that would make it possible to share them in a database. Figure 13 shows an extract of part of the performance specifications for a vehicle. Shared management of performance specifications in a database has reduced the labor involved in sharing the details of studies and the results of calculations, reducing the time needed for these procedures. Figure 14 shows a breakdown of these reductions. The time required for the processing of the calculation results and the sharing of the report, corresponding to the second half of the performance design process, has been reduced to around 1/70th of the previous time.

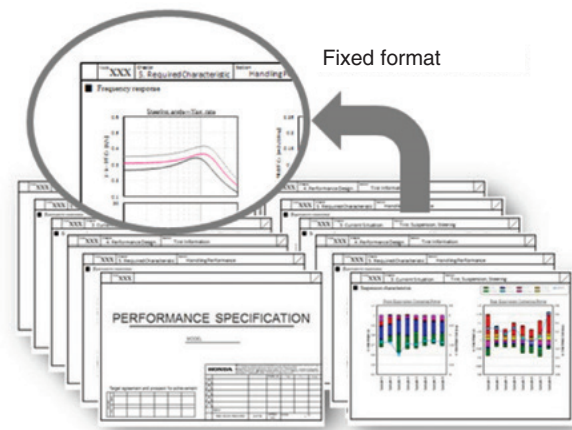


Fig. 13 Performance specifications

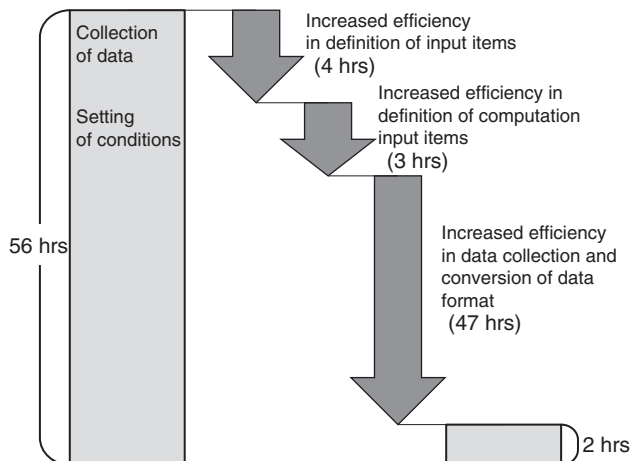


Fig. 12 Enhanced input efficiency

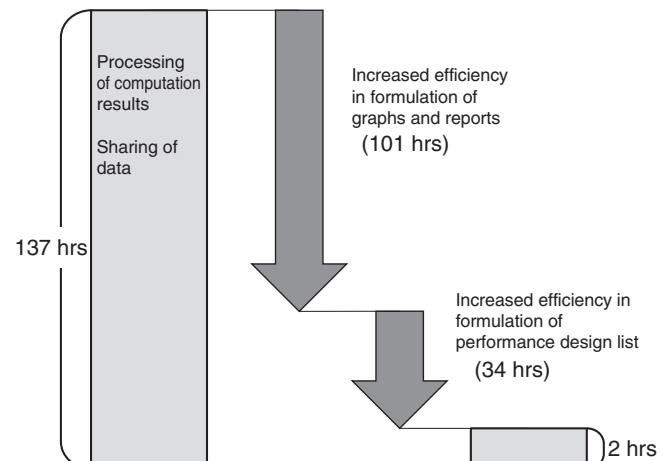


Fig. 14 Enhanced output efficiency

5. Examples of Implementation of Performance Design

5.1. Studies towards Increased Dynamic Performance in S660

The concept for the S660 was to create a vehicle displaying agile handling, making it possible for users to enjoy full-fledged sports performance in a lightweight car. In order to underline this concept, the main points of focus were responsiveness to initial steering input and turning performance when the wheel was turned, and dynamic performance targets were set for handling. At the same time, it was also necessary to realize adequate stability for a sports car. Targets for stability at high speeds were therefore also set. It was necessary to realize all of these targets simultaneously. Specific performance design target values were set as follows:

- (1) Stability at high speeds: Realization of a stability factor of at least $0.001 \text{ s}^2/\text{m}^2$ and a handling capacity of at least 220 m/s^2 at 100 km/h ⁽²⁰⁾⁻⁽²⁴⁾.
- (2) Agile handling: Realization of a maximum lateral acceleration of at least 10.4 m/s^2 and a maximum rear axle slip angle of 10 deg or less during a 100 km/h J-turn^{(20), (22)-(24)}.

The major issue in the case of performance design for the S660 was efficiently determining the specifications that would simultaneously realize both of these targets from among an enormous number of potential combinations.

It was necessary to develop the S660 in a short period of time, but because a large number of components necessitated specialized design, the degree of freedom in design was high, and an enormous number of combinations of individual components was therefore available in seeking to realize target performance. MBD was employed from the initial stages of the development process. Simulation studies of some tens of combinations of specifications were conducted in a short period of time, and specifications that were considered optimal from the performance design perspective were finally proposed. The two graphs in Fig. 15 show an example of the allocation of specifications in order to realize target performance. The graphs show only the most representative indicators⁽²⁴⁾. Like the S660, in the case of the development of vehicles that differ considerably from other mass-production vehicles in terms of factors such as basic specifications and drive type, it is challenging to obtain basic values because little data exists to provide a reference for characteristic values or property values of detailed sections. Given this, if the process of seeking optimal specifications from among countless combinations of component characteristics while simultaneously studying large numbers of target values had been undertaken experimentally, using trial and error, it is probably unlikely that specifications making it possible to realize the targets would have been determined within the development period for this model. The developed method made it possible to proceed with the study of different specifications while

simultaneously verifying large numbers of performance demands from the beginning of the development process for the S660⁽²⁵⁾.

5.2. Balancing Emergency Handling Performance and Ride Comfort in the CLARITY FUEL CELL

A vehicle provided with advanced technologies, the CLARITY FUEL CELL uses fuel cells to generate electricity and drive a motor. Another target was to realize an extremely quiet and comfortable vehicle. In addition to this, the goal was to create a package that would reconcile a practical layout for each component with design features. This represented an unfavorable condition in relation to reducing the vehicle's moment of inertia. It is also necessary to employ a range of devices in FCV, increasing the weight of the vehicles against gasoline vehicles of the

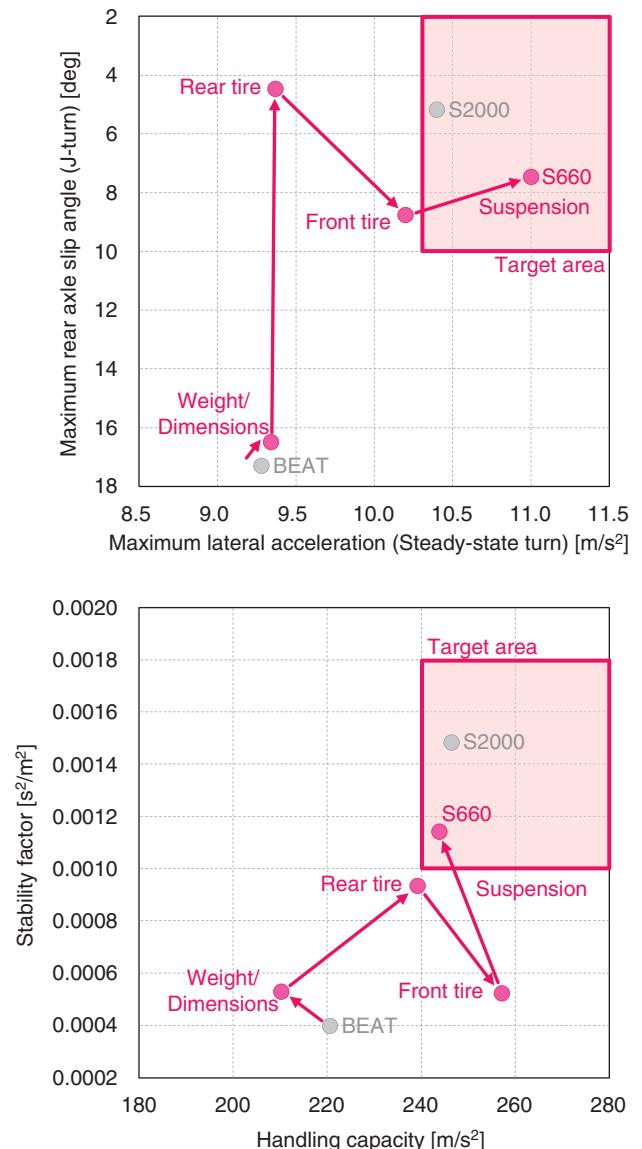


Fig. 15 Performance design for S660

same class. In other words, developers were presented with the task of realizing equivalent dynamic performance to a normal vehicle of the same class in a heavy FCV with a high moment of inertia. Because the battery stack that supplements the fuel cell stack and the drive motor were particularly heavy, the layout of these components would have a particularly great effect on dynamic performance, and would be the key to balancing ride comfort with quietness. The performance design target values for dynamic performance set under these various restrictions were a delay time in lateral acceleration response during a double lane change (DLC) of no more than 0.15 sec in 1st and 0.175 sec in 2nd. Figure 16 shows delay time in lateral acceleration response during a DLC.

A countless number of combinations of tire, suspension, and other component characteristics could be considered towards the realization of the targets discussed above, and seeking specifications that balance ride comfort and quietness while also satisfying the target packaging through trial and error would be no easy task. Because the layout of the stack and the motor and the stiffness of the mounts would result in major changes in ride comfort and quietness, it was essential to conduct studies of dynamic performance while also taking these factors into consideration. Using the developed method, it was possible to conduct computations for some tens of combinations in a short period of time while considering the balance with performance demands other than dynamic performance. Figure 17 shows an example of the results of one study, demonstrating that the developed method is effective even in developments of this type, in which the development proceeds in tandem with studies attempting to realize a balance with performance demands other than dynamic performance and with the demanded specifications⁽²⁵⁾.

5.3. Studies towards the Realization of Increased Stable Handling Potential in the Linear Region for the 2014 model year FIT

As a global model, the 2014 model year FIT (2014 FIT) would be marketed throughout the world, and the aim for

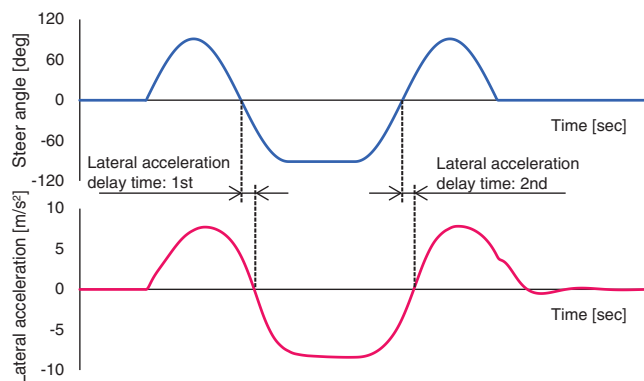


Fig. 16 Lateral acceleration during DLC

the development was therefore to simultaneously realize specifications for all global variations. It was therefore necessary to seek combinations within a short period of time that would satisfy target performance demands from a diverse range of specifications that differed for each region in which the vehicle would be sold. It had also been decided that a wide range of derivative models, including sedans, wagons, SUV, and minivans, would also be developed using the platform developed for the 2014 FIT. It was thus essential to boost the performance potential of the vehicle from the initial stages of development in order to respond to derivative models with a wide variety of shapes. MBD using the developed method was applied to the development, and because it was possible to refer to data for the 2008 model year FIT (2008 FIT), calculation conditions could be formulated and target performance set rapidly for the 2014 FIT. The 2014 FIT was the first model to be developed with full-scale application of performance design using MBD to the study of stable handling in the linear region.

Because MBD was employed in studies for the 2014 FIT, it was possible to conduct calculations for all specifications for all global models, and to verify the potential of all specifications to realize target values using simulations. In other words, it was possible to verify the potential of the base vehicle in relation to derivative models without tests in actual vehicles.

The ability to practically apply MBD in the development of a mass-production vehicle made it possible to also simultaneously establish potential outlooks in relation to the performance of derivative models being developed in parallel. For example, studies were conducted of the performance of the suspension in a state of rebound in order to help ensure high road clearance for the SUV model; studies were conducted in order to further increase ride

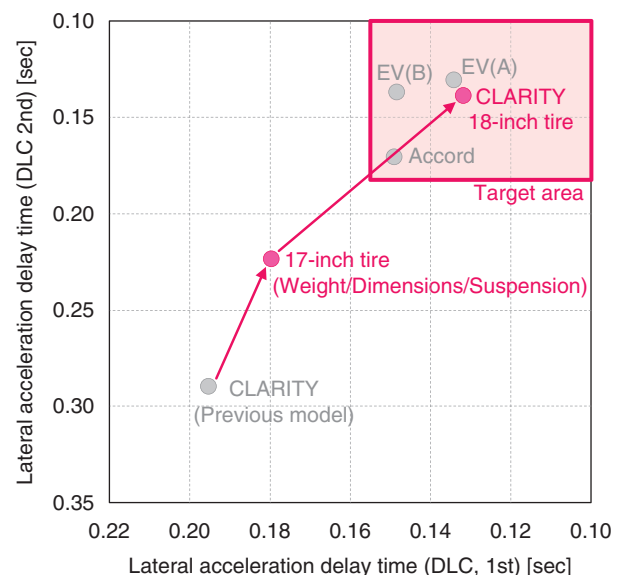


Fig. 17 Performance design of 2016 model year FCV

comfort in the sedan model; and, during the development of the minivan model, studies were conducted of the dimensional specifications providing the maximum overhang for the FIT platform, seeking the optimal specifications in relation to target values for dynamic performance. Figure 18 shows a diagram of computation studies conducted for the 2014 FIT, including derivative models. The use of the developed technologies made it possible to conduct the large number of studies shown here within a short period of time.

5.4. Studies towards the Realization of Increased Handling Potential in the Limit Region for the 2017 model year CR-V

The major issue in terms of dynamic performance in the development of the 2017 model year CR-V (2017 CR-V) was to realize stable handling in the limit region for all specifications⁽²⁶⁾. A wide range of variations were set for the 2017 CR-V, encompassing a range of powerplants (including turbo, diesel, and hybrid), 4WD and FWD drive types, two- and three-seat seating layouts, 17-inch, 18-inch and other tire sizes, and a panorama roof option. A large number of potential specifications therefore existed, all of which were predicted to have a major effect on dynamic performance. Using MFD to conduct studies towards the realization of target performance in relation to all of these specifications would not have been easy. For the performance design of the 2017 CR-V, it was necessary to conduct studies not only towards the realization of stable handling in the linear region, but also stable handling in the limit region, within a short period of time.

Because data for the preceding 2012 model year CR-V (2012 CR-V) were available in the case of the 2017 CR-

V, it was possible to rapidly set calculation conditions and performance design target values. By contrast with the development of the 2012 CR-V, simulation studies proceeded using models defined for the three levels at basically the initial stage of development, allowing developers to proceed with sufficient consideration not only of efficiency, but also of accuracy. Figures 19⁽²¹⁾ and 20⁽²⁸⁾ show simulation results obtained at the time. Here, steer angle amplitude expresses the rate of multiplication of the steering wheel angle (defined as 1[A]) when turning

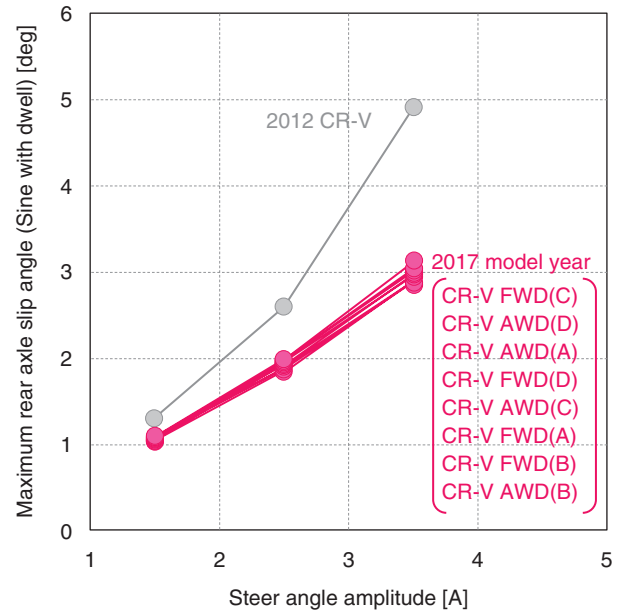


Fig. 19 Study of emergency handling

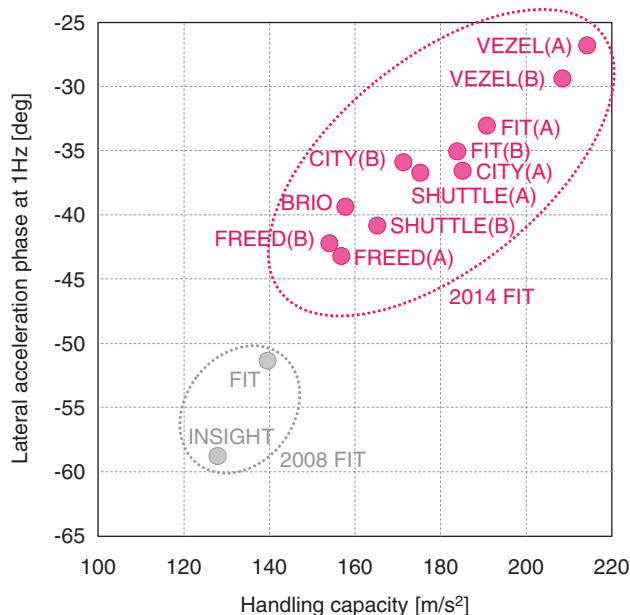


Fig. 18 Performance design of 2014 FIT

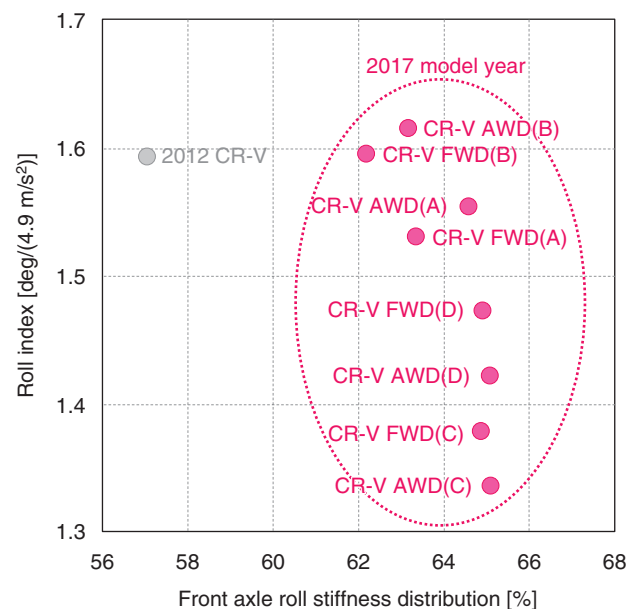


Fig. 20 Performance design for 2017 CR-V

in a fixed circle at a lateral acceleration of 2.9 m/s^2 ⁽⁵⁾. By contrast with the previous model, when only the results of studies of representative models were available for theoretical study, for the 2017 CR-V, simulation studies were conducted for all of the large number of specifications. During the development of the 2017 CR-V, it was demonstrated that performance design using MBD could be applied to a wide range of studies, extending even to nonlinear elements, in this case the tires and bump rubber bushes⁽²⁷⁾.

The four examples discussed above demonstrate, based on actual results, that the developed technologies can be applied to a wide range of elements within the chassis development process for mass-production vehicles.

6. Conclusion

The simulation output time for MBD in function design and performance design stages was reduced to around 1/50th of the previously required time, making it possible to apply MBD to the development of mass-production vehicles. The research process can be summarized as follows:

- (1) Standard vehicle simulation models for performance design were defined for three levels.
- (2) Defining the necessary input items for simulations increased the efficiency of procedures, reducing the time required for the first half of the performance design process to approximately 1/30th of that previously needed.
- (3) Defining performance specifications as the format for simulation results and creating a database of performance specifications reduced the time expended up to the sharing of results, corresponding to the second half of the performance design process, to approximately 1/70th of that previously needed.
- (4) The time required for function design and performance design using MBD has been reduced to approximately 1/50th of that previously needed.

Afterword

The development of the method discussed in this paper has enabled practical application of MBD in the chassis development process for mass-production vehicles. The authors hope in future to apply MBD to the full range of models using this method, and to expand the scope of function design and performance design methods using MBD to areas including dynamic performance in the driving/braking region and passenger comfort, seeking to realize a highly efficient automotive development process.

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