

Lap Time Simulation Technology for Performance Design during Production Car Development

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ABSTRACT

A lap-time simulation technology for circuit driving compatible with performance design technologies employed during the development of production vehicles has been developed. The method creates vehicle models using data employed in the model-based development of production vehicles, and by combining these with models of driving and road surface conditions, reduces the computation time necessary for lap time simulation. The ability to define two models using the circular arc and whole curve transition methods makes it possible to apply the method in the performance design of production vehicles using all drive types. The method enables treatment of lap times during circuit driving as one item in the study of specifications during performance design in the development of production vehicles. The application of the method in the study of specifications during the development of the new NSX and the CIVIC TYPE R demonstrated the validity of the concept and the effectiveness of the method.

1. Introduction

Model-based development is an effective means of increasing the efficiency of the automotive development process at a time when the complexity of systems is rapidly increasing⁽¹⁾. Model-based development is also a means of reducing the time necessary for performance design, and the application of these technologies not only reduces development time, but also allows examination of new performance factors. One such representative performance factor is lap time during circuit driving.

Lap time simulations have conventionally been employed in the development of racing vehicles. Because lap time simulations have been created mainly for the purpose of calculating and predicting lap times as a substitute for conducting measurements in actual vehicle tests, the major focus has been on minimizing error in an attempt to help ensure that calculation results conform closely to values measured in driving tests. As a result, it is necessary to use not only highly detailed vehicle data, but also a high volume of vehicle-related peripheral data, such as data concerning the course that is the subject of the simulation, detailed vehicle aerodynamic characteristics, changes in temperature, and the specific characteristics of the driver's vehicle operation. The complexity of these

simulation models results in long computation times, and it has therefore not been an easy matter to use lap time simulations in performance design during the development of production vehicles^{(2), (3)}.

While it is possible to consider model-free development based exclusively on the results of lap time measurements conducted during driving tests, in order to help ensure safety, this necessitates the possession of an exclusive test circuit, and the use of drivers with high levels of skill. The frequent use of tests involving so many restrictions would affect the development of other production vehicles, and is therefore impractical. As a result, lap time has not been employed as a focus item in performance design for production vehicles other than in the case of special models based on a concept of appealing to a high level of dynamic performance.

However, the ability to treat lap time as a performance factor in performance design during the development of production vehicles would be beneficial from the perspective of the efficient development of high-performance vehicles. Doing so would require taking a different perspective to conventional lap time simulations, and output calculation results in a short period based on limited data. The application of the technologies of model-based development was therefore considered as a response to this necessity.

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2. Aims for Developed Technology

Employment of lap time simulations in the development of production vehicles would require conducting calculations based on easily obtainable data, as well as studying specifications within a limited period of time. General applicability making it possible to employ the method for all production vehicle types would also be necessary. Taking these demands into consideration, the following four items were set as development targets:

- (1) Ability to generate vehicle models using data employed in model-based development of production vehicles;
- (2) Reduction of the computation time necessary for output of results, enabling use of the method for the performance design during the development of production vehicles;
- (3) Realization of the ability to use the method for performance design of the three types of standard production vehicles, i.e. front-wheel, rear-wheel, and four-wheel drive; and
- (4) Ability to output, in addition to lap time results, results for other indices of dynamic performance including maximum acceleration, maximum lateral acceleration, maximum deceleration, and maximum speed.

3. Mechanism for Lap Time Simulation

Because standard vehicle dynamics simulations run models on horizontal planes without specifying a course, the only elements necessary for the simulations are those related to vehicle conditions. By contrast, for lap time simulations it is necessary to define three main elements in the model: in addition to elements related to vehicle conditions, these are elements related to driving conditions and elements related to the state of the road surface.

3.1. Elements related to Vehicle Conditions

In this paper, elements related to vehicle conditions refer to basic elements of vehicle dynamic performance, specifically driving (acceleration performance), turning (cornering performance), and stopping (braking performance)⁽⁴⁾. The representative indices that express these basic elements of performance are acceleration, lateral acceleration, and deceleration, the respective maximum values of which are termed maximum acceleration, maximum lateral acceleration, and maximum deceleration.

To study acceleration performance, maximum acceleration is calculated using models of the powertrain system created using elements including the weight of the vehicle, the torque characteristic of the engine or motor, the gear ratio, and the diameter of the tires. At the same time, maximum acceleration is also calculated using a chassis system model created using the weight of the vehicle, the vehicle's center of gravity, the front-rear force characteristic of the tires, and the front and rear distribution of drive force.

Actual acceleration at any point is calculated by comparing the results of the two, and subtracting the driving resistance component (air resistance, rolling resistance, etc.) from the lowest.

With regard to cornering performance, maximum lateral acceleration is determined based on the weight of the vehicle, the vehicle's center of gravity, the cornering characteristic of the tires, the distribution of roll stiffness, suspension stiffness, the suspension alignment characteristic, and downforce. Actual maximum lateral acceleration at any point is calculated by subtracting driving resistance including air resistance and rolling resistance from the results.

In the case of deceleration performance, maximum deceleration is calculated based on the weight of the vehicle, the vehicle's center of gravity, the front-rear distribution of braking force, and the front and rear force characteristic of the tires. As in the calculation of acceleration performance, actual deceleration at any point is calculated by subtracting driving resistance including air resistance and rolling resistance from the results.

The discussion above has provided an overview of the elements related to vehicle conditions necessary for lap time simulations. The details are identical to those for the Level 1 and Level 2 simulations defined in a previous paper⁽¹⁾.

3.2. Elements related to Driving Conditions

Driving conditions are conditions that specify what locus the vehicle traces on the circuit course (termed the "driving locus" below), the timing of acceleration, and the timing of deceleration. Driving locus models affect the results of lap time simulations, and a variety of methods of creating the models have therefore been proposed. Regardless of which method is used, however, if an ideal driving locus is determined based on calculations alone, in the absence of reference data, it becomes necessary to separately create an optimization logic, increasing the computational burden and necessitating an extended period of time⁽⁵⁾⁻⁽⁷⁾. In the present case, the use of a high volume of driving locus data obtained from actual measurements as reference data and the definition in advance of driving loci derived statistically using specific rules, in order to reduce computation time, was effective in reducing the computational burden.

The driving locus on any circuit can be classified into two domains: straight sections and corner sections. The definition of driving loci in the corner sections is of particular importance, because it has a significant effect on the results of lap time calculations. Conventionally, the driving locus models employed in lap time simulations have been limited to a single type, and the rules employed have become very complex when they are applied to all circuits and the performance design of all vehicles in development. In order to address this issue, the present research defined two types of driving locus model, and employed either

model in response to specific circumstances. The methods of generating these two types of model have been termed the circular arc method and the whole transition curve method.

3.2.1. Circular arc method

The circular arc method is a method of specifying the entire driving locus by approximating the driving locus on straight sections as a straight line and the driving locus on corner sections as an arc. Figure 1 shows the radius of curvature of the driving locus specified by the circular arc method as a graph. In the straight sections, the radius of curvature becomes infinitely large, and its value cannot be defined. In the corner sections, the radius of curvature takes a fixed value, and is shown as an arc. The advantage of this method is that acceleration and deceleration can be completed on the straight sections, and lateral acceleration is constant on the corner sections. This makes it easy to understand the effect of vehicle characteristics in the straight sections and the corner sections. In addition, the models are simple, and the computational burden is low.

3.2.2. Whole transition curve method

In the whole transition curve method, the driving locus on the straight sections is approximated by a straight line, as in the circular arc method, but the driving locus on the corner sections is not specified using arcs, but rather using particular curves. Here, these curves are termed transition curves. Transition curves are determined statistically from past measurement data; optimum paths are determined in order to help ensure that no discontinuities occur in the

radius of curvature^{(5), (8)}. Figure 2 shows an example of the radius of curvature of a driving locus specified using the whole transition curve method expressed as a graph. The radius of curvature of the transition curve from the straight to the apex of the corner decreases monotonically, and after the apex of the corner increases monotonically towards the next straight section. The advantage of this method is that it is possible to gradually change the radius of curvature when connecting the straight and corner sections, producing a driving locus that is closer to reality than the circular arc method. Computation results generated by this method correspond particularly well with the results of actual driving tests in situations involving the frequent occurrence of scenarios in which lateral acceleration gradually increases as deceleration gradually decreases, or in which acceleration gradually increases as lateral acceleration gradually decreases. In addition, calculations for the entire corner section are able to consider the tire friction circle⁽⁹⁾ characteristic, and the method is therefore suited to use in cases in which braking force and side force are simultaneously produced on the tires (Tire slip conditions: Combined). However, the whole transition curve method uses a higher volume of data than the circular arc method, and the computational burden is therefore higher. In addition, because the method does not distinguish between a state in which the vehicle is braking and driving in a straight line and a state in which the vehicle is performing a steady-state turn, it is not easy to clearly distinguish the effect of vehicle characteristics in relation to straight sections and corner sections in studies of specifications for performance design.

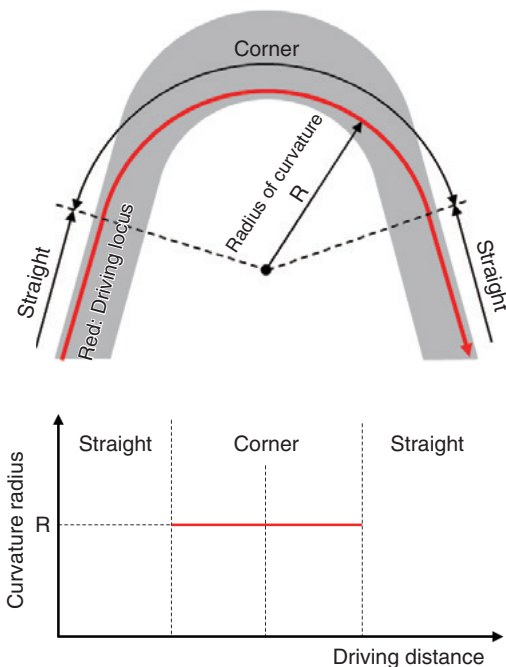


Fig. 1 Circular arc method

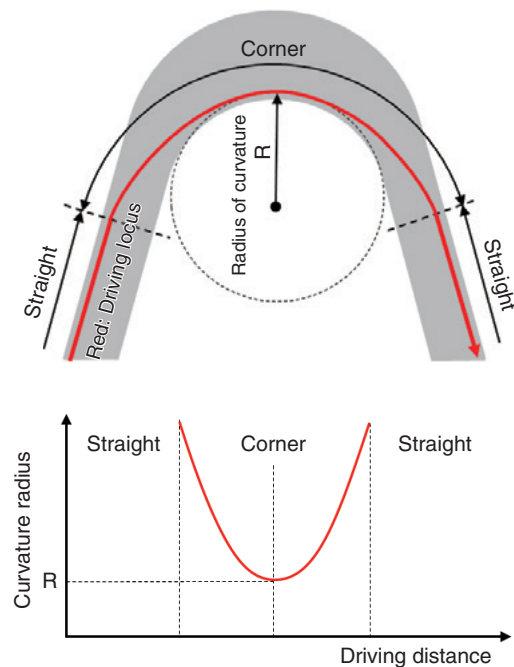


Fig. 2 Whole transition curve method

Table 1 Characteristics of two methods

Method	Definition of corner	Tire slip conditions	Characteristics
A	Circle	Pure	Contribution of straights and corners to lap time is clear
B	Transition curves	Combined	Radius of curvature is continuous (Locus is close to actual drive)

A: Circular arc method
B: Whole transition curve method

Table 1 summarizes the specific characteristics of each method, as discussed above.

3.2.3. Specification of driving loci for simulations

Actual driving loci can be considered as comprising straight lines, arcs, and transition curves connected in complex ways. In principle, the use of the two methods described above enables comprehensively expressing all driving loci. The circular arc method offers considerable advantages in that the method simplifies understanding of the effect of vehicle characteristics in relation to straight sections and corner sections, and the computational burden is low. This is why lap time simulations employed in performance design generally use the circular arc method. However, in the case of front-wheel drive vehicles fitted with high-power engines and high-performance brakes, in corner sections powerful forces act simultaneously on the front wheels in the longitudinal and lateral directions, and if calculations are conducted without consideration of the

friction circle characteristic, the level of divergence from the actual state becomes greater and error cannot be ignored. This issue can be addressed by using the whole transition curve method for simulations in these cases. The use of the two methods therefore makes it possible to conduct lap time simulations for all vehicles.

With regard to driving conditions, in addition to specifying the driving locus, it is necessary to specify the timing of deceleration, cornering, and acceleration. In the simulations under consideration, which divide the driving locus into straight sections and corner sections, the point at which deceleration ends corresponds to the point at which lateral acceleration occurs, and the point at which acceleration begins corresponds to the point at which lateral acceleration is 0. With the vehicle speed at these points as a reference, in the corner sections, the circular arc method defines a cornering motion with the vehicle's speed fixed at the maximum lateral acceleration. Figure 3 shows lateral acceleration and vehicle speed output during cornering under the conditions of the circular arc and whole transition curve methods as graphs. Beneath the graphs, the figure shows images of the directions of the forces generated within the tire friction circles.

With regard to vehicle speed on the straight sections, from the point at which the vehicle leaves the corner section and lateral acceleration becomes 0, vehicle speed is increased by maximum acceleration, and at the point at which lateral acceleration increases at the next corner

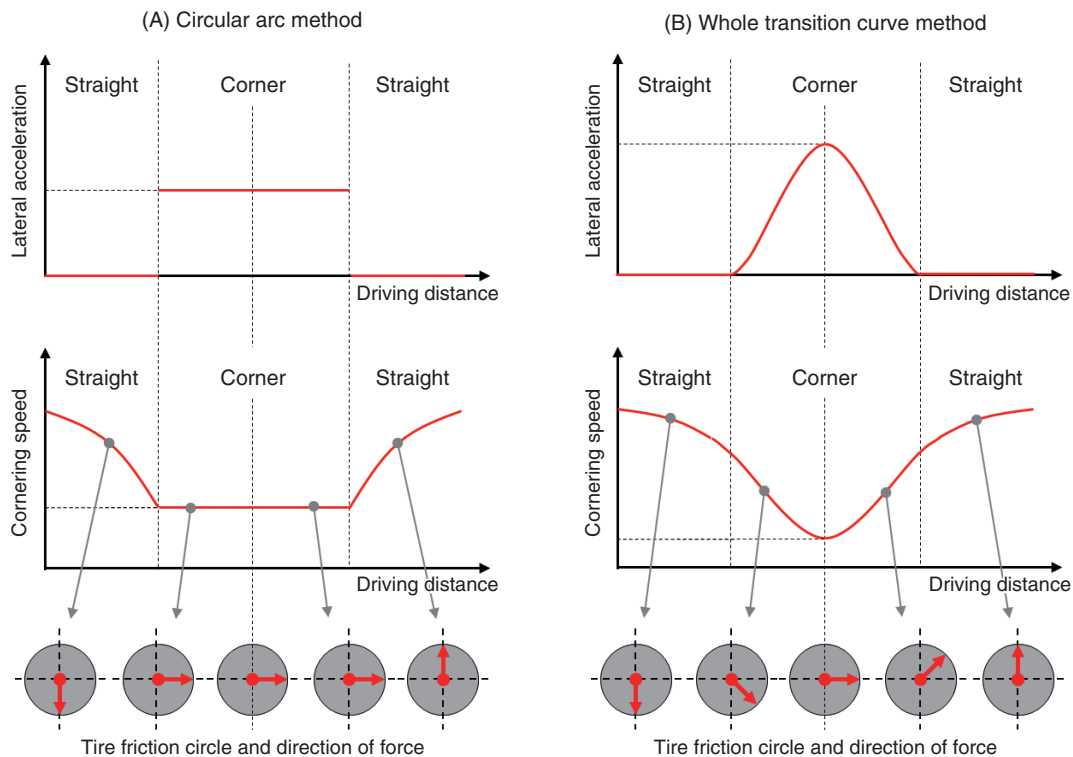


Fig. 3 Comparison of two methods

section, vehicle speed is reduced by maximum deceleration in order to realize the maximum cornering speed. Figure 4 shows changes in speed between straight sections for the circular arc method. This figure shows that the driving locus calculated by increasing vehicle speed by maximum acceleration with point x1 (commencement of acceleration) as the reference, and the driving locus calculated by reducing vehicle speed by maximum deceleration with point x2 (completion of deceleration) as the reference, cross at point x3. The concept is the same for the whole transition curve method.

The specification of driving conditions as discussed above makes it possible to specify the driving locus at any point of a circuit lap as shown in Fig. 5. Because vehicle speed can be continuously calculated, lap time can also be calculated simultaneously. This makes it possible to reduce the simulation computation time without the use of optimization logic or other methods, and to specify driving

loci able to be employed in effective lap time simulations for use in the performance design of production vehicles.

3.3. Elements related to the Shape of the Road Surface

The shape of the road surface is made up of slope (the gradient in the direction in which the vehicle is proceeding), undulation, and cant (the gradient in the lateral direction of the vehicle). The slope of the road surface affects acceleration and deceleration, and cant affects maximum lateral acceleration.

The left-hand side of Fig. 6 shows the slope of the road surface. This image shows the gradient of the road surface in relation to the direction in which the vehicle is proceeding. Acceleration and deceleration when the vehicle is advancing or braking are affected by gravitational acceleration in response to the degree of the slope, and

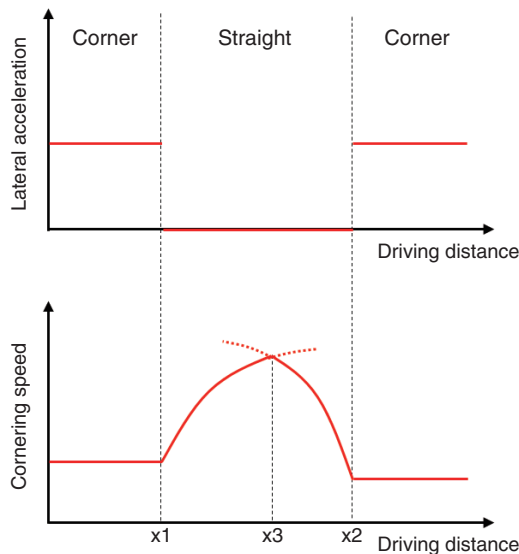


Fig. 4 Speed on straight

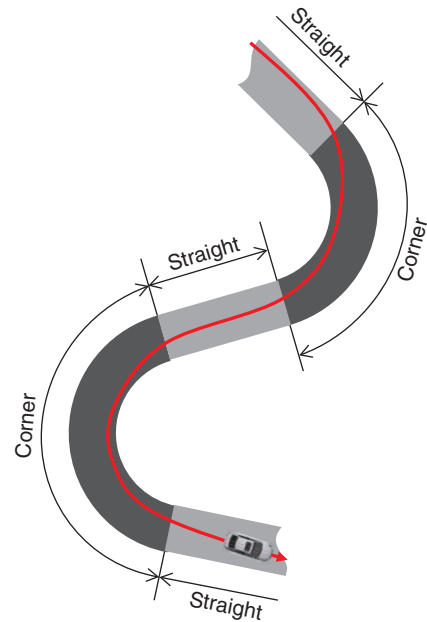


Fig. 5 Straights and corners

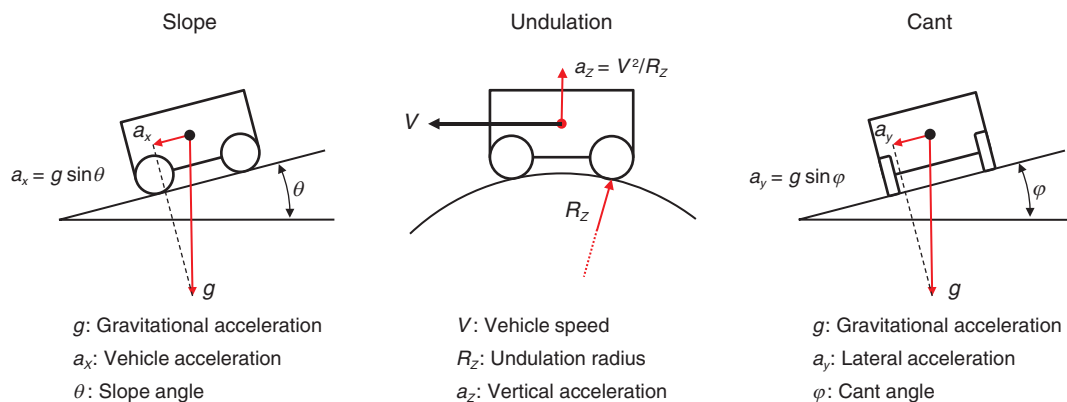


Fig. 6 Elements related to road surface shape

change as a result. The image in the middle of Fig. 6 shows the undulation of the road surface. When a vehicle is driving on an undulating road of this type, when the vehicle is proceeding on a convex section, a force acts in the upwards direction to lift the vehicle; when a vehicle is proceeding on a concave section, a force acts in the downward direction, as if pressing the vehicle against the road surface. When the lifting force in the upwards direction is acting on the vehicle, the friction circles of the tires are reduced; when the pressing force in the downwards direction is acting on the vehicle, the friction circles of the tires increase. As a result, maximum acceleration and deceleration as well as maximum lateral acceleration are affected. The right-hand side of Fig. 6 shows cant. Cant is a left-right inclination of the road surface in relation to the direction in which the vehicle is proceeding. As in the case of slope, when the vehicle is cornering, lateral acceleration is affected by the degree of cant and changes as a result.

4. Verification of Effectiveness and Examples of Application

This section will discuss the development of two models featuring significantly different drive types and specifications to provide examples of the use of lap time simulations in vehicle studies. The first of these was the new model NSX. This was a high-performance four-wheel drive vehicle, with high loads generated on the rear wheels. The second was the 2015 model CIVIC TYPE R. This was a high-performance front-wheel drive vehicle, with high loads generated on the front wheels (Table 2). Lap time simulations will be discussed for two circuits: the Tsukuba Circuit, on which large numbers of lap time measurements have been conducted during the development of past production vehicles; and the Nürburgring Circuit, which is frequently used to provide benchmarks during vehicle development. MATLAB was employed for the simulations.

4.1. NSX Development

The NSX is Honda's representative high-performance super sports car, and was developed with the aim of realizing the world's highest level of dynamic performance. Targets were set for the top level not only in lap time, but also in all other indicators of dynamic performance, including maximum acceleration, maximum deceleration, maximum lateral acceleration, and maximum speed.

Figure 7 shows the results of a lap time simulation and actual lap time measurement data presented graphically as a driving history, both for the Tsukuba Circuit. The red solid line shows calculation results, and the blue broken line shows actual measurement data. The graph indicates that the results of the developed lap time simulation conform closely to the results of actual driving tests.

Lap time, maximum speed, maximum acceleration, maximum deceleration, and maximum lateral acceleration can be derived from the driving history produced using

Table 2 Specifications of NSX and CIVIC TYPE R

	NSX	CIVIC TYPE R
External dimensions L × W × H (m)	4.490 × 1.940 × 1.215	4.390 × 1.880 × 1.460
Wheelbase (m)	2.630	2.600
Weight (kg)	1800	1380
Drive type	Engine and Motor/AWD	Engine/FWD
Maximum power (Engine/Motor) (kW)	373/200 System maximum power: 427	228
Maximum torque (Engine/Motor) (Nm)	556/366 System maximum torque: 646	400

calculation results. From driving history data, it is possible to consider factors such as the characteristics of the circuit, including the speed ranges used overall, the frequency of straights and corners, and the degree of acceleration and deceleration.

Figure 8 shows a graph produced from a lap time simulation for the Tsukuba Circuit, with lap time and maximum speed used as respective indicators on the horizontal and vertical axes. The graph plots results for six different specifications, based on calculations conducted

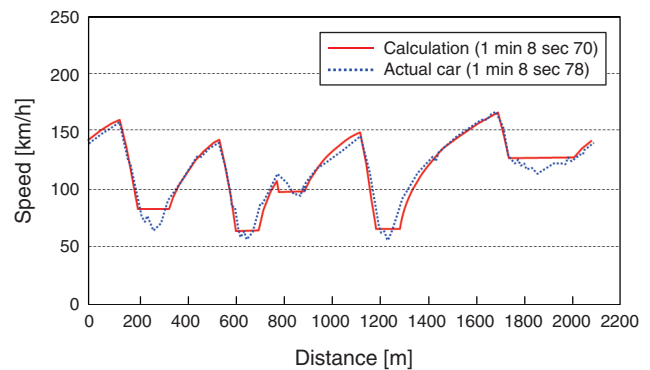


Fig. 7 Driving history

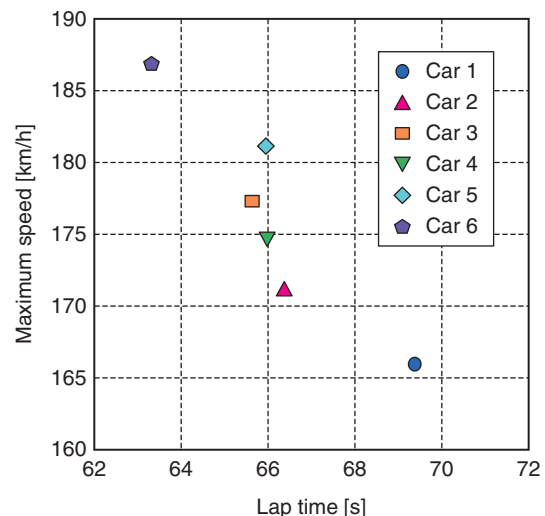


Fig. 8 Lap time and maximum speed

for Cars 1 to 6, representing different combinations of tire size, aerodynamic characteristics, and weight distribution conditions. Because shorter lap time and higher maximum speed results are preferred, the results for Car 6 plotted in the upper left of the graph indicate that this car displays the highest level of performance.

Figure 9 shows results for maximum lateral acceleration expressed as a bar graph. Higher maximum lateral acceleration can be considered to produce higher performance, and higher results are therefore preferred in this bar graph.

The horizontal axis of Fig. 10 shows maximum deceleration determined by the chassis and tires with the brake elements removed, and the vertical axis shows maximum acceleration determined by the chassis and tires with the engine elements removed. This makes it possible to compare the effect of the chassis and tires on acceleration and deceleration performance. For both indicators, higher values show higher performance, with the chassis whose results are plotted in the upper right of the graph displaying the highest potential.

The results shown in Figs. 8 to 10 discussed above are representative results output by lap time simulations. During performance design in the initial stage of the development of the NSX, these graphs were compared while conducting performance design for a variety of specifications. The characteristics of each component, including engine power, cornering of the tires, air resistance and downforce, suspension alignment, and battery layout were studied, and specifications that satisfied target performance on the Tsukuba Circuit were determined.

Turning to examples of performance design using the Nürburgring Circuit, Fig. 11 shows total times for straights and corner sections presented as a graph, with the different sections classified by color. Results for total time for the straights are shown in green, and results for the total time

for the corners are shown in red. Cars 1 to 4 show the results of analyses of the driving loci of four representative sports car models manufactured by competitors. These results indicate whether it is more effective to apply measures for the straights or for the corners. The graph suggests which component it would be most effective to apply measures to in order to reduce lap time. For example, if the vehicle were driving on a circuit made up exclusively of corners, the ranges in the corner sections would be the most frequent, and it would be possible to effectively reduce lap time through measures that increase speed during cornering. The study of specifications for the NSX was based on

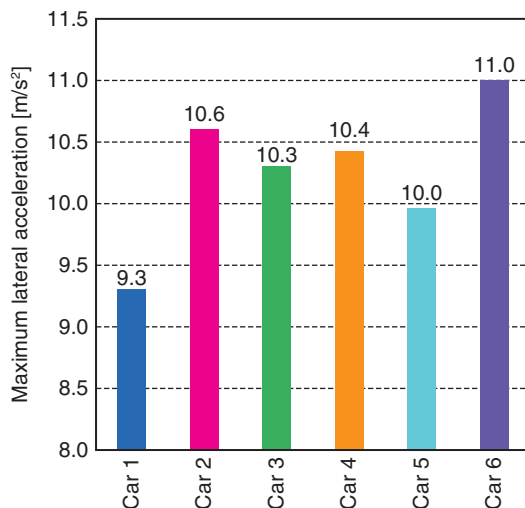


Fig. 9 Maximum lateral acceleration

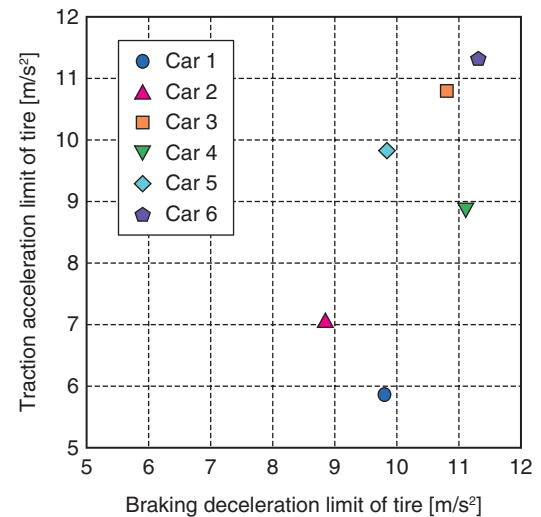


Fig. 10 Tire traction and deceleration limits

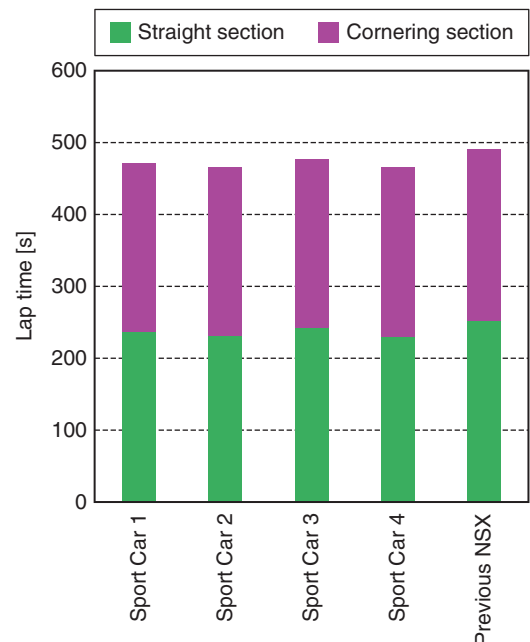


Fig. 11 Time for straight and corner

considerations of this type, and optimal specifications were pursued based on a variety of perspectives before the ultimate specifications were determined.

Figure 12 shows the results of a study conducted for performance design in corner sections. The graph shows the effect of the battery layout for the hybrid motor, the use of aerodynamic devices such as spoilers, and of tire size. Studies of this type made it possible to obtain potential achievement of 234 sec or below set as the total target time in the corner sections.

In the actual development process, respective specifications were determined on the basis of these simulation results, and a prototype vehicle was created. This prototype was able to achieve the target time in actual driving tests. Figure 13 shows a graph of results for various powerplant specifications studied during performance design, and the effect of the specifications applied in order to realize the targets for lap time and maximum speed.

4.2. Development of CIVIC TYPE R

The CIVIC TYPE R is a representative Honda high-performance front-wheel-drive vehicle. The concept for the vehicle was to achieve the fastest lap time for a front-wheel drive vehicle on the Nürburgring Circuit. In practical terms, this meant a lap time of within 7 min 50 sec (470 sec). The process of performance design in relation to the lap time of the CIVIC TYPE R was basically the same as that for the NSX, but while the NSX was a four-wheel-drive vehicle, the CIVIC TYPE R employed front-wheel drive. The front wheels therefore supported both cornering side force and braking and drive force in the corner sections, making the way in which the front tire friction circles were used an important factor. The use of the whole transition

curve method employing friction circle models for lap time simulations therefore generated values closer to actual vehicle measurements for the CIVIC TYPE R. The vehicle therefore provides a representative example of a case in which performance design employed both lap time simulations using the circular arc method and those using the whole transition curve method.

Figure 14 shows a graph of forces produced by a tire contact patch, measured in order to specify the tire friction circles for the whole transition curve method.

Figure 15 compares lap times for the CIVIC TYPE R on the Tsukuba Circuit calculated using the circular arc method (red solid lines), calculated using the whole transition curve method (red broken lines), and actually measured lap times (blue broken lines). This graph shows that the whole transition curve method produces calculation

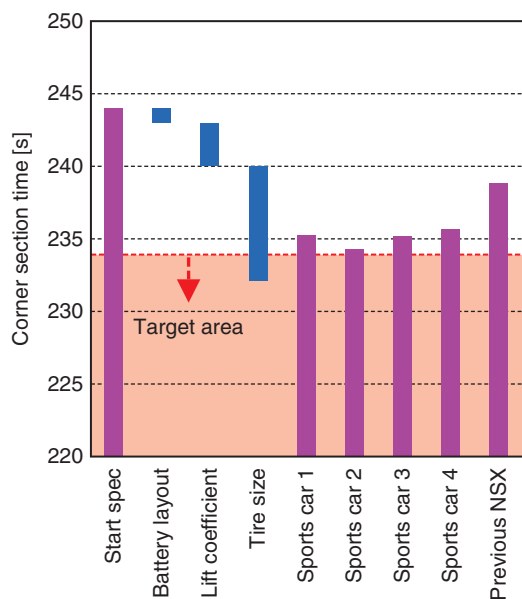


Fig. 12 Results of study of specifications for NSX

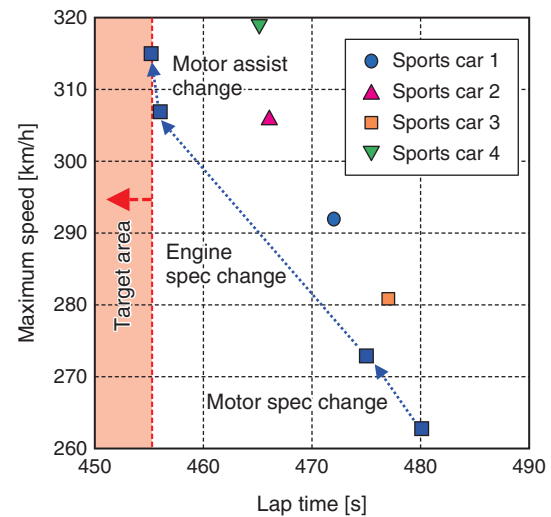


Fig. 13 Lap time and maximum speed

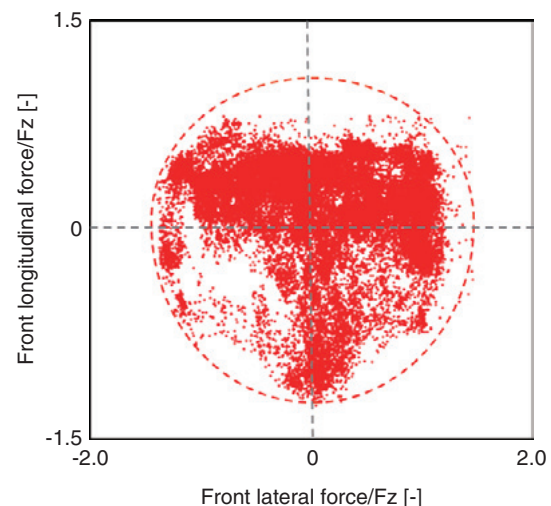


Fig. 14 Force generated on road surface

results closer to the results of actual measurements than the circular arc method. Calculation results produced by the circular arc method tend to diverge from actually measured values especially in the case of powerful front-wheel-drive vehicles like the CIVIC TYPE R. In such cases, it is possible to study the effects of performance design with the necessary accuracy by creating calculation models using the whole transition curve method.

Figure 16 shows a graph of the effect allotted to each component in realizing the target lap time for the CIVIC TYPE R on the Nürburgring Circuit. This graph indicates

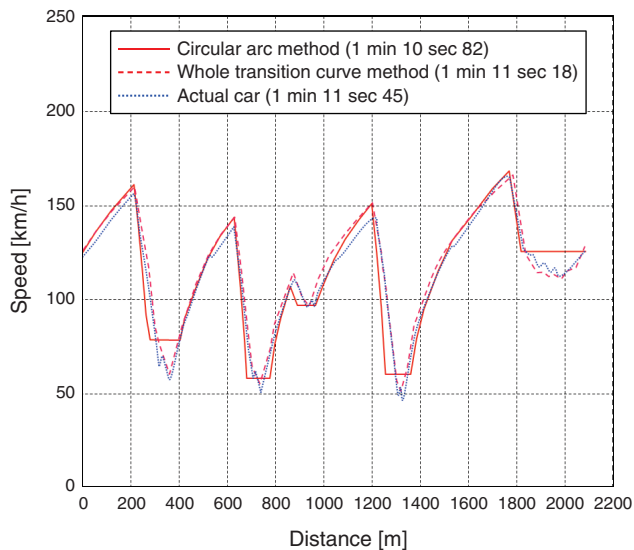


Fig. 15 Comparison of results of two methods and actually measured values

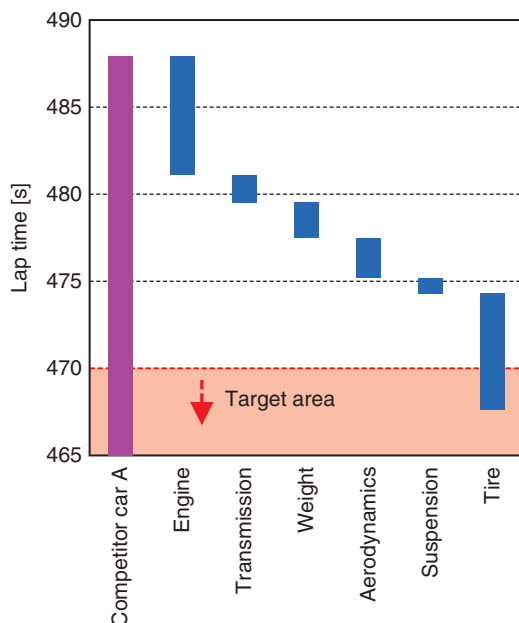


Fig. 16 Deployment of system for CIVIC TYPE R

that applying measures in the areas of engine power, the transmission gear ratio, vehicle weight, the aerodynamic characteristic, the suspension specifications, and the tire size, enabled the potential realization of the target lap time. As this demonstrates, the use of lap time simulation made it possible to allot performance elements to each component at the stage of performance design.

5. Conclusion

This paper has presented two examples of the use of lap time simulations for the Tsukuba and Nürburgring Circuits in the development of production vehicles. These examples have demonstrated the validity of the authors' concept of lap time simulation models and the effectiveness of the simulation technologies.

The research discussed in the paper can be summarized as follows:

- (1) A lap time simulation tool using conditions defined during the model-based development of production vehicles has been created.
- (2) The specification of elements related to driving conditions and to road surface conditions has reduced computation time, making it possible to apply lap time simulations to performance design in the development of production vehicles.
- (3) The generation of two models using the circular arc and whole curve transition methods enables creation of lap time simulation environments able to respond to all vehicle drive types.
- (4) In addition to lap times, the method is able to output values for other performance indicators, including maximum acceleration, maximum lateral acceleration, maximum deceleration, and maximum speed.

The developed tool is able not only to predict lap times as a substitute for vehicle tests, but also to allocate performance demands for the characteristics of each component based on lap time targets, and thus to proceed effectively with system design, demonstrating that the tool can be applied in the development of production vehicles.

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