Technologies for Enhancement of Dynamic Performance of Formula One Vehicle

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ABSTRACT

No matter how superb the performance of the powerplant, unless that power can be transmitted efficiently and effectively through the tires to the track surface, a race vehicle will not have a competitive edge. The most recent technologies for the enhancement of the dynamic performance of Formula One vehicles are developed with a focus on maximizing tire performance. The tires used in Formula One are designed for good performance only within an extremely narrow range of conditions in terms of parameters such as tire contact state and tire temperature, in order to enhance the performance of the tires to the limit. Therefore, understanding and controlling these conditions is an important issue in the development of enhancement technologies for the dynamic performance of Formula One vehicles. This paper will discuss suspension design and vehicle setup, two factors that affect tire performance, and the development of a tire model to function as their theoretical basis.

1. Introduction

Development programs to enhance the dynamic performance of Formula One vehicles are conducted in two stages. The first is the design stage for vehicle performance. At this stage, the vehicle concept and targets for the various elements of dynamic performance are established based on performance analyses of Honda vehicles and other teams' vehicles, and vehicle components enabling these targets to be realized are designed.

The second stage is vehicle setup on an actual circuit. The dynamic performance of Formula One vehicles varies with the layout of the circuit, track conditions, and atmospheric conditions, and a vehicle will therefore not always display identical performance. Accordingly, at this stage, element parts with varying specifications and mechanisms that enable vehicle characteristics to be varied are prepared, and the vehicle's dynamic performance in actual circuit driving is optimized by means of their application and coordination.

While vehicle design determines the potential dynamic performance of the vehicle, setup on the circuit enables the vehicle to reach that potential in response to circuit conditions and race strategy. The use of these two stages enables the vehicle to display a high level of dynamic performance in a race.

The paper will discuss the concepts employed in suspension design and setup, factors that affect tire performance, and will consider the development of a tire model to serve as their theoretical basis.

2. Suspension Design

The suspension plays an important role in maximizing the performance potential of the tires. In Honda's third Formula One era, suspension development was conducted making maximal use of techniques fostered in the development of mass production vehicles. In particular, specifications were set for the scrub radius, caster trails, and other aspects of king pin geometry using identical concepts to those employed in mass production vehicles, and their usefulness was verified.

Elements specific to Formula One are a tire characteristic in which the tires perform well under an extremely narrow range of conditions, and an aerodynamic characteristic in which vehicle behavior that is determined by the suspension plays an important role. Based on these considerations, development was conducted as follows:

(1) Optimization of initial camber, camber gain, and camber change with steering angle in accordance with tire characteristics
(2) Development of tire air temperature control technique for stabilization of tire pressure
(3) Development of load transfer control for adjustment of mechanical balance, in order to enhance tire warm-up performance
(4) Development of geometry enabling maximization of aerodynamic performance

As one example aspect of suspension development, this paper will discuss the development of a front pushrod on upright (FPROU) suspension that is designed

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to maximize tire performance by means of control of wheel load for all four wheels.

2.1. Overview of FPROU

The Formula One steering characteristic basically uses understeer (US) to increase stability during high-speed cornering and oversteer (OS) to enhance turn-in performance during low-speed cornering. Suspension design exploited the nonlinearity of the angles of rotation of the rocker arms in relation to the vertical motion of the pushrods to induce a high level of nonlinearity in the wheel rate of the front wheels (a rising rate). This increased front roll stiffness during high-speed cornering, when a strong downforce is acting, thus enabling use of US.

During Honda's third Formula One era, the company was successful in enhancing turnability during low-speed cornering by mounting the front pushrods on the uprights rather than the lower wishbones in order to produce a characteristic that varied the mechanical balance (the front-rear allocation of lateral load transfer during turning) in relation to the steering angle (Fig. 1).

2.2. Load Transfer Mechanism during Turning

When the vehicle is statically steered, the front inner wheel will normally be subjected to a downward load, due chiefly to the effect of the angle of the casters. Because the motion in the front roll direction that this induces is restricted by the rear suspension, the wheel loads for the four wheels are transferred diagonally. It is known that because the load transfer produced by this geometric motion is added to the load transfer produced by the front-rear allocation of roll stiffness and the anti-force geometry when the vehicle is turning, load transfer can be controlled by controlling the trajectory of contact patch lift when the steering wheel is turned. In conventional suspensions, increasing the caster angle will reduce the load transfer at the front of the vehicle.

This section will focus on the inner turning wheels in order to consider the changes produced when the pushrods are mounted on the uprights. Because there is virtually no change in damper stroke when the steering wheel is turned, pivot N of the pushrod on the rocker side (Fig. 1) can be considered to be fixed. This means that pivot M of the pushrod on the upright side is confined on the sphere surface with pivot N at its center. When pivot M is positioned to the rear of the kingpin (Fig. 2), pivot M rotates around the axis of the kingpin and shifts towards the center of the vehicle when the steering wheel is turned. Because the pushrod is at an anhedral angle, it is necessary for the upright to shift in a downward direction. In the same way, if the outside wheel is considered, the upright shifts in an upward direction.

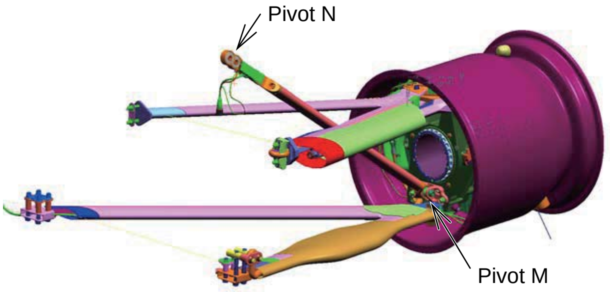

Fig. 1 Front pushrod on upright suspension

Figure 3 shows the amount of contact patch lift against toe angle. When the M pivot is offset to the rear, the same effect can be obtained as when the caster angle is increased. As a result, there is a comparative reduction in front load transfer when the vehicle is turning. By contrast, when the M pivot is offset to the front, the same effect can be obtained as when the caster angle is reduced.

The exploitation of the mechanism described above enabled control of the mechanical balance that is dependent on toe angle without restriction by geometric considerations such as the position of the kingpin axis, and played an important role in helping to inhibit US during low-speed cornering.

In addition, when the M pivot was offset in the left-right direction (y) using the same mechanism, the upright rose together with the inner and outer turning wheels when the steering wheel was turned, lowering the height of the vehicle (Fig. 4). This effect was particularly marked in the large steering angle range.

2.3. Dynamic Performance Simulation

Figure 5 shows the results of prediction of changes in mechanical balance in a vehicle motion simulation using ADAMS. When a positive offset is introduced, i.e.,

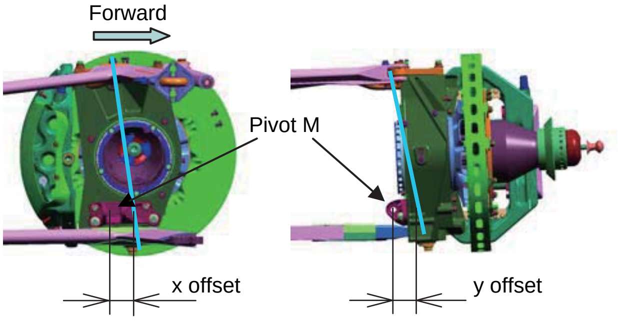

Fig. 2 Definition of pushrod offset

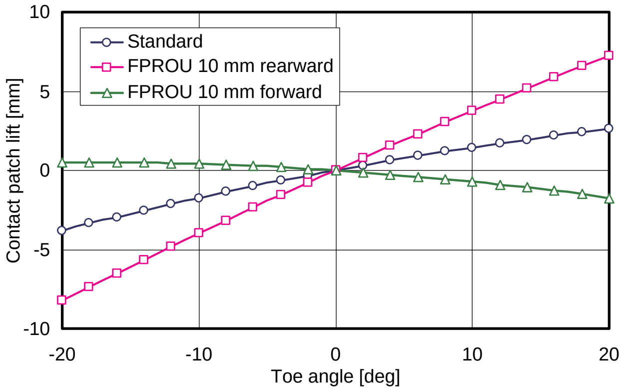

Fig. 3 Change in lift against toe angle

when the M pivot is offset to the rear of the kingpin axis, the mechanical balance shifts to the rear, and the steering characteristic tends towards OS. The degree of change in the mechanical balance increases in proportion to the level of offset.

2.4. Track Tests and Application in Races

Track tests were conducted on the suspension system designed and manufactured on the basis of the simulations in September 2005 on the Jerez circuit. The tests demonstrated the superiority of the new suspension system, as it matched the targets set for it in helping to inhibit US during low-speed cornering and consistently bettering lap times against the base vehicle. Based on these results, the suspension system was employed in races from the Japan Grand Prix in 2005 onwards.

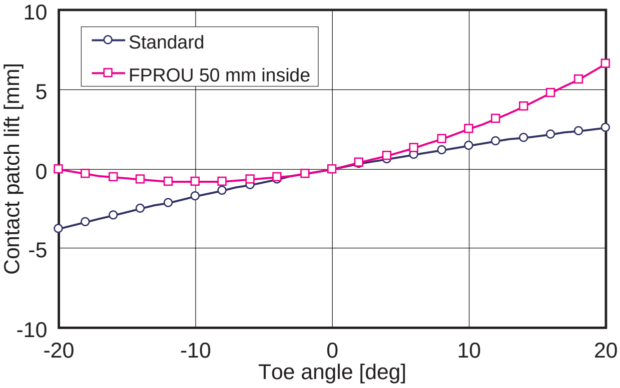

Fig. 4 Change in lift against toe angle (y-direction offset)

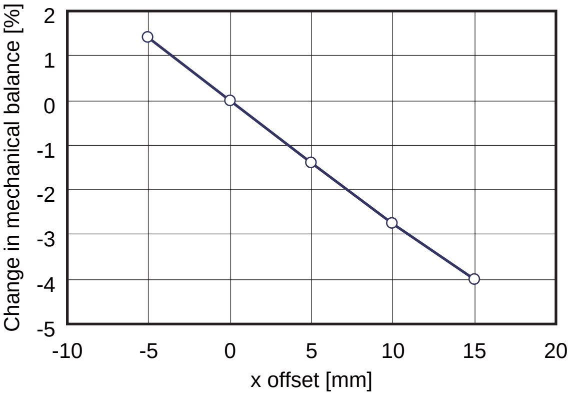

Fig. 5 Change in mechanical balance with x-direction offset

3. Concept of Vehicle Setup

This chapter will focus on vehicle setup, and will consider the concept for the setup of the 2006 RA106 vehicle, which became the basis for later vehicle setup.

Having taken second place in the 2004 World Constructors' Championship, Honda commenced the 2005 race season determined to win the title, but the 2005 vehicle displayed low braking stability. The drivers demanded increased stability during braking, and the hydraulic control was modified to greatly inhibit the differential motion of the differential gears (ultimately, spools were fitted to mechanically connect the left and right wheels). Due to this increased US during turn-in, the mechanical balance was setup to shift towards the rear wheels in order to enhance turn-in performance. However, this increased the load on the outer rear wheels during cornering, generating sudden snap OS resulting in the rear wheels slipping when the vehicle accelerated coming out of a corner. This made the vehicle's cornering traction performance fall behind that of other vehicles (Fig. 6).

In addition, the increased load on the rear tires brought about a degradation of the tire compound, and stability and traction performance declined with each lap. In addition, the setup produced a vicious circle in which a decline in cornering speed also reduced the temperature of the front tires, further increasing US and thus resulting in a decline in dynamic performance.

3.1. Method of Formulation of Setup for RA106

The main issue with regard to the setup of Honda's 2005 Formula One vehicle was that engineers had become process-focused and shortsighted in their quest for local optimal solutions, resulting in the inability to exploit the potential for the dynamic performance that should be expected from the vehicle.

Accordingly, the formulation of a concept to enable vehicle setup to be conducted in a strategic fashion was focused on in the development of the RA106. This meant a rigorous process in which the performance elements that should be enhanced in setup were clarified, methods of achieving these targets were quantitatively analyzed, effects and levels of sensitivity were predicted, taking in pros and cons, and these predictions were verified in track tests. The process aimed, by establishing the orientation for the setup on the desk and using track tests for verification, to avoid falling into the trap of localized optimization as had been the case when the setup was successively altered on the basis of the results of individual tests.

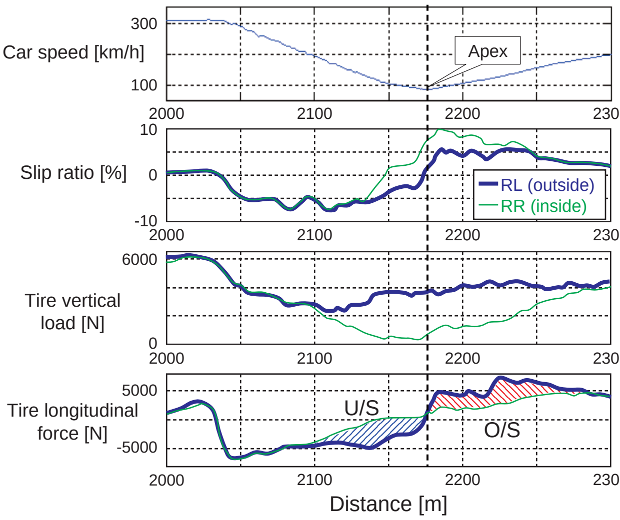

Fig. 6 Cornering conditions in 2005

In addition, setting milestones in the formulation of the setup and designing and implementing track test plans on this basis helped to enable a reliable verification process.

3.2. Concept of Setup of RA106

The dynamic performance of Honda's 2005 Formula One vehicle was analyzed, and the following performance elements were selected as targets for the RA106, based on considerations of maximizing tire performance by optimizing the total setup of the vehicle:

(1) Enhancement of cornering traction performance
(2) Reduction of degradation of rear tires
(3) Achievement of increased grip force by increasing temperature of front tires

3.3. Methods of Achieving Targets

A simulation using a tire model was employed in an analysis to enable engineers to determine how to achieve the targets listed above using the following elements of vehicle setup, which determine dynamic performance:

- Front axle weight distribution (W/D)
- Front axle downforce distribution (CoP)
- Front axle mechanical balance (M/B)
- Lateral distribution of rear braking and driving force (Diff)

Figure 7 shows the results of an analysis of changes in traction performance when cornering in each speed range. The forward shift of M/B has the greatest effect in enhancing traction performance during low-speed cornering, with W/D having the next greatest effect. The CoP makes a high contribution in the high-speed range. Figure 8 shows the results of an analysis of changes in traction performance when each of the elements of the setup is varied. In the case of M/B, traction performance increases virtually linearly up to a shift of approximately 25% forward. Because increased traction performance from low speeds upwards would make a significant contribution to enhanced lap times, forward M/B was made the main element in the achievement of enhanced traction performance.

With forward M/B, the overall steering balance would become US. Figure 9 shows estimates of the amount of adjustment of W/D and CoP necessary to achieving this balance. Despite the fact that sensitivity differs with cornering speed, each parameter displayed a largely linear response in relation to the degree of change in M/B. Figure 10 shows the results of an analysis of the effect of the lateral distribution of longitudinal forces on the rear wheels produced by the differential gear on the steering balance. During low-speed cornering, the US generated by forward M/B could be compensated by differential control, but this did not have sufficient effect during high-speed cornering, and it would therefore be necessary to compensate for US in combination with another element of the setup. It was judged that the combination of forward M/B and rearward W/D would contribute to enhanced traction performance, and this was therefore selected as the best strategy.

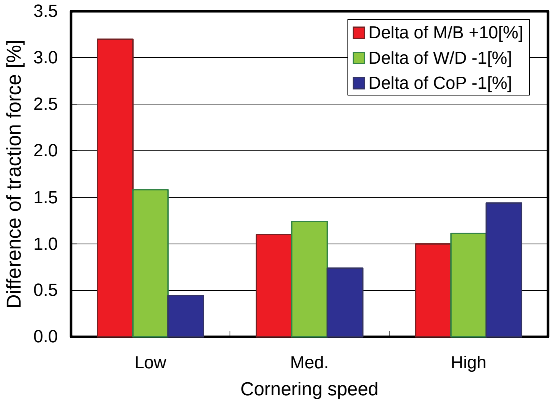

Fig. 7 Traction enhancement with setup changes

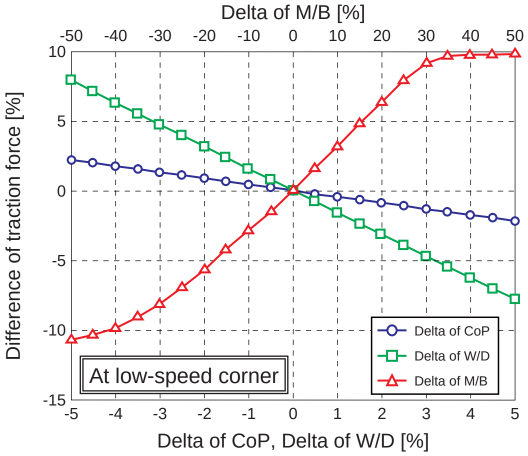

Fig. 8 Traction change with setup sweep

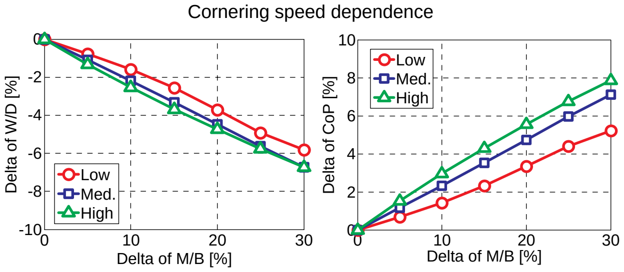

Fig. 9 Relationships in setups for achievement of equivalent steer balance

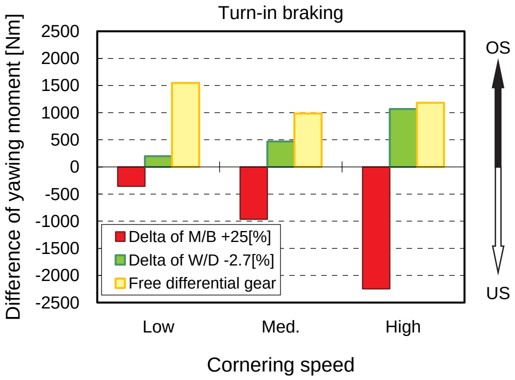

Fig. 10 Effect of differential gear on steer balance

Figure 11 shows the results of an analysis of the change in tire surface temperature during cornering when the M/B was varied. It was estimated that forward M/B could cause the temperature of the front outside tire, which is dominant during cornering, to increase, and that the tire’s grip force would increase as its temperature approached the necessary temperature range. In addition, because the temperature of the rear outside tire would decrease, this method could also be expected to control the degradation of the tire compounds due to excessive temperatures.

Based on the results of the analyses discussed above, the proposed setup for the RA106 was formulated as follows:
(1) Forward mechanical balance
(2) Rearward weight distribution
(3) Differential gear control during cornering

3.4. Verification of Effects

The effects of the RA106 setup that had been formulated on the desk were verified in track tests conducted on a variety of courses from December 2005 to February 2006.

Figure 12 shows a comparison of traction force during low-speed cornering in track tests conducted on the Jerez circuit. For this test, the M/B of the RA106 was increased by 6.4% and its W/D reduced by 1.5% against the 2005 vehicle in the setup. As a result, the average traction force of the RA106, averaged over 10 laps, increased by approximately 10%. Figure 13 shows a comparison of section time for cornering traction during low-speed cornering, with the RA106 setup reducing the vehicle’s average time per corner by 0.05 sec. As a result, the lap time of the RA106 was reduced by an average of 0.74 sec per lap (Fig. 14). These results indicated that the cornering traction performance of the RA106 had been enhanced.

Figure 15 shows the results of an analysis of tire degradation. Data for which track conditions and atmospheric conditions could be regarded as identical was isolated from data collected in multiple track tests of the 2005 vehicle and the RA106 conducted for the same periods of time. Lap times for each lap were averaged from this data. These average lap times were taken to be representative values for change in lap time, and the degree of degradation in lap times was compared for the vehicles. Taking into consideration the difference in the weight of the vehicles, a simulation was used to calculate the sensitivity of lap time to vehicle weight,

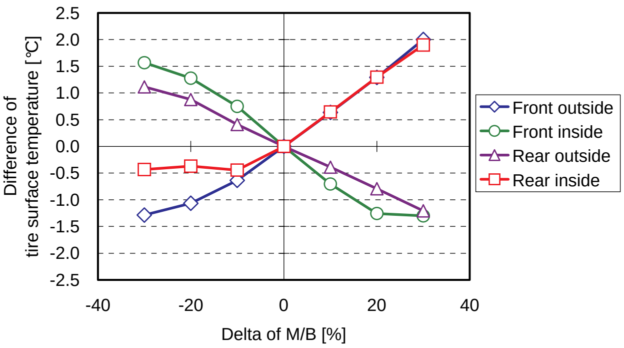

Fig. 11 Estimation of change in tire surface temperature

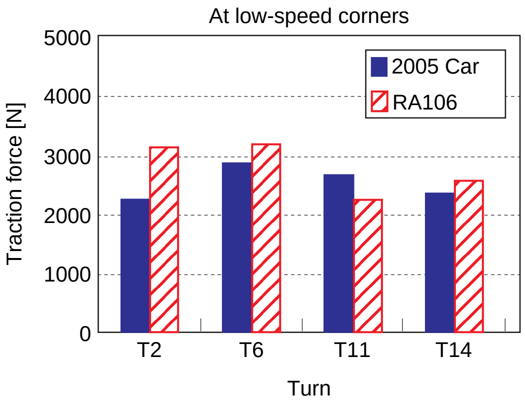

Fig. 12 Comparison of traction force

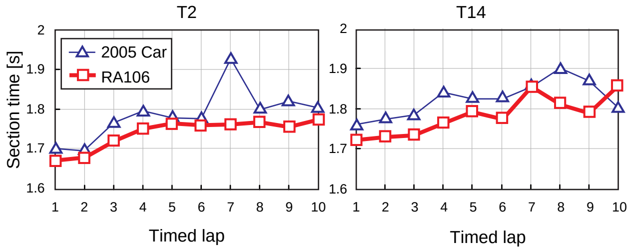

Fig. 13 Section time during corner acceleration

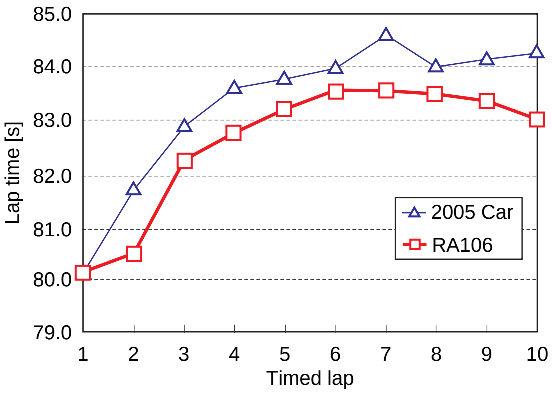

Fig. 14 Comparison of lap time

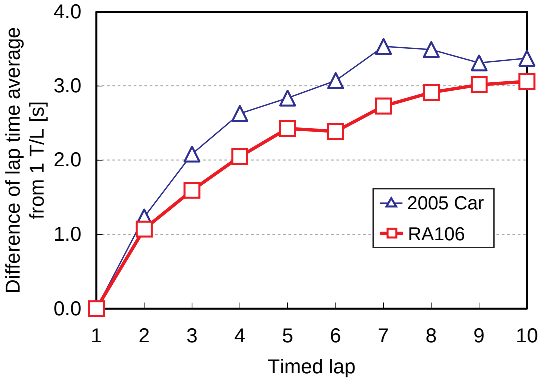

Fig. 15 Analysis of tire degradation from perspective of lap time

and the lap times were converted to represent vehicles of the same weight. The results of the comparison showed that the level of deterioration in lap time was reduced by an average of approximately 0.48 sec for the RA106, indicating that the degradation of the tires had been controlled.

Figure 16 shows the results of a comparison of front tire temperature conducted in the same way, using data from track tests with largely identical track and atmospheric conditions. The tests were conducted on the Jerez circuit, which features a large number of right turns. The temperature of the left front tire, which more frequently worked as the outer tire, increased by an average of approximately 16°C, while the temperature of the right front tire increased by approximately 5°C.

The results of these analyses confirmed that the RA106 setup had performed as speculated, increasing cornering traction performance, controlling tire degradation, and increasing grip force by raising the temperature of the front tires.

3.5. Summary of Concept of Vehicle Setup

The elements of the RA106 setup which would lead to performance enhancements were determined through analysis of the 2005 vehicle, and a simulation employing a tire model was used to study a setup that would actualize these elements. The effects of the setup were verified in track tests, confirming that the setup accorded with the goals established for it. Following this verification of the effects of the RA106 setup in tests conducted during winter, the setup was used as the base for all vehicle setups from 2006, and contributed to Honda’s victory in the 2006 Hungary Grand Prix.

While vehicle setup had previously relied to a great extent on comments from drivers and the experience of the engineers involved, these results demonstrated that a logical approach, based on a tire model, was effective. The necessity for the development of a more sophisticated tire model capable of predicting performance under all conditions therefore increased.

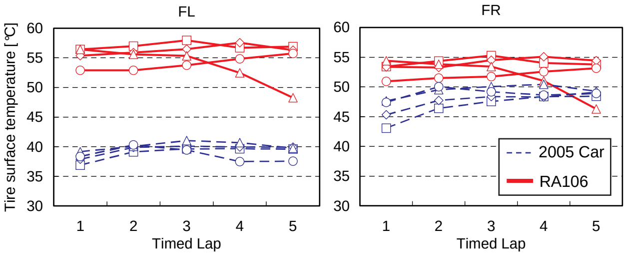

Fig. 16 Front tire surface temperature

4. Development of Tire Model with Coupled Calculation of Force and Temperature

Tire performance has a considerable effect on the dynamic performance of Formula One vehicles. The achievement of enhanced dynamic performance necessitates a quantitative understanding of tire performance, and vehicle design and setup that maximize tire performance under all conditions. Regulations stipulate that the setup be performed by Saturday morning in race week, and it is therefore necessary to perform the setup with consideration of factors including changes in environmental conditions during the qualifying sessions on Saturday afternoon and the finals on Sunday. This necessitates a model capable of calculating at a sufficient rate of accuracy the force generated by the tires under a variety of driving conditions, including load, alignment, and track surface temperature. The performance of Formula One vehicle tires is in particular affected by the surface temperature and the internal temperature of the tires, and this necessitates the use of a model that considers the effect of temperature, and is able to perform coupled calculations of force and temperature in response to changes in tire input due to environmental temperature and driving conditions.

The ability to simultaneously analyze tire force and temperature would represent a significant advantage not only to considerations of vehicle setup and tire performance, but also to considerations including race strategy, such as warm-up performance when a safety car is on the track, and degradation due to heat.

The Magic Formula is one well-known tire model, but this model does not include a temperature element, making it unable to calculate the effect of temperature changes resulting from driving conditions on tire force. Tire suppliers also provide tire models, but their insides are concealed, in practice inhibiting any increase in the accuracy of the models or modification for use by the race team.

It was judged that in order to excel over other teams in the area of vehicle dynamic performance, it would be necessary to possess, as an in-house developed technology, a tire model able to perform coupled calculations of force and temperature, and to use this tire model as the basis for a technology enabling prediction and analysis of dynamic performance.

4.1. Structure of the Model

4.1.1. Model concept

Considering the use of the model in vehicle setup at the circuit in addition to vehicle design, the development of a model with a good balance between calculation accuracy and speed was established as a target. The elements with the greatest effect on the accuracy of calculations of tire forces were isolated and modeled to enable this target to be met.

Tire forces are chiefly determined by the structural deformation of the tire and the friction characteristic between the road surface and the tire. The friction coefficient of the tires is changed significantly by environmental conditions and driving conditions, including the road surface roughness, dust on the road surface, tire surface temperature, tire slip speed, rubber wear, and thermal degradation. Accordingly, characteristics such as structural deformation and heat transfer, which could be modeled on the basis of theoretical concepts and the results of bench tests, were separated in the model's structure from elements such as the friction coefficient, which are dependent on actual driving conditions, with the parameters for the latter being identified from actual vehicle data. This helped to enable the creation of a more realistic and more accurate model.

4.1.2. Force model

The model treated deformation of the tire contact patch as divided into a belt section and a tread rubber section.

Belt deformation was approximated by expression as a quadratic function in relation to the position of the tire contact patch in the longitudinal direction. The deformation obtained in this manner was corrected using the tire side force, self-aligning torque, internal pressure, and longitudinal force.

With regard to the deformation of the tread rubber section, the adhesive contact area (the area of elastic deformation) of the contact patch was calculated from the relationship between the maximum deformation of the tread rubber, as determined by the elastic modulus, the static friction coefficient, and the contact surface pressure, as well as the necessary deformation, as determined by the tire slip angle, slip ratio, and degree of belt deformation. The rest of the contact patch was considered a sliding contact area (Fig. 17).

The forces on the tire are determined in the adhesive contact area by the elastic modulus of the rubber and the degree of deformation, and in the sliding contact area by the slip friction coefficient and load. At this stage, a model was formulated in which the elastic modulus was defined as bulk temperature functions (bulk temperature will be discussed below), the static friction coefficient as surface temperature functions and contact surface pressure functions, which is to be corrected based on its distribution in the direction of the tread. The slip friction coefficient was further defined as tire slip speed functions in the model.

Using this method, the tire force in the adhesive and sliding contact areas were calculated, and their synthesis enabled calculation of the final tire force.

4.1.3. Thermal (temperature) model

The cross-sectional structure of the tire was formularized as a one dimensional node model divided into three layers, a tread surface layer, tread bulk rubber layer, and carcass/tread belt rubber layer, with each layer at a single temperature.

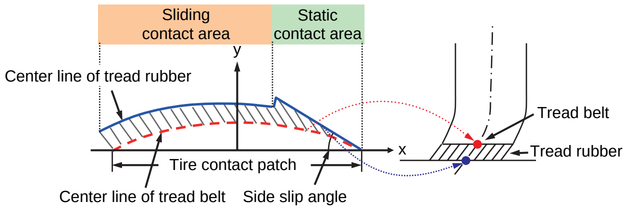

Fig. 17 Deformation model for tire contact patch

In addition, the work performed by the tire was input as heat chiefly in the tread surface layer for the sliding contact area and in the tread bulk rubber layer for the adhesive contact area. The rolling resistance of the tire was treated as heat generated in the tread bulk rubber layer.

Heat transfer between the three layers, convection heat transfer to the air, and heat conduction to the road surface at the contact area are all calculated to enable calculation of the temperature of each layer. Heat transfer by radiation was considered to have represented 2% or less of the total figure in comparison to heat convection and conduction, and was therefore omitted from the model (Fig. 18).

4.2. Identification of Parameters

4.2.1. Method employed

The difference between the calculation results for force and moment from the model, obtained using time series data from track tests for parameters including wheel load, slip angle, slip ratio, and camber angle, and the target data were treated as objective functions, and parameters were identified using an optimization method to minimize this difference. Parameters that changed with the degradation of the tires, such as maximum friction coefficient, were identified for each lap, while parameters that did not change, such as the temperature characteristic, were identified as a single value for all the track test data. Measurement results from sensors and the results of calculations using a combination of sensor results and bench test results or theoretical values (in the case of parameters including wheel load and slip angle) were used as the data necessary for parameter identification.

The following two methods of identification were employed, depending on the target.

(1) Method using the results of 6-component wheel force measurements

The results of 6-force measurements (longitudinal force, side force, self-aligning torque) were used as targets. Because the accuracy of identification was increased and the level of variation reduced the greater the diversity of combinations of parameters such as wheel load and alignment, data for both the left and right tires were employed in the parameter identification.

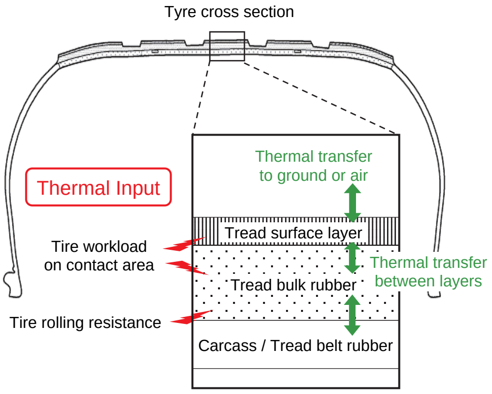

Fig. 18 Tire thermal model

(2) Method using vehicle’s dynamic states

Vehicle’s dynamic states (longitudinal acceleration, lateral acceleration, and yaw moment) measured using sensors were employed as targets. The vehicle’s dynamic states were calculated using a variety of data including calculation results from the tire model, vehicle specifications, and figures for air resistance and tire rolling resistance, and parameters were identified simultaneously for the front and rear tires that enabled these dynamic states to be matched with the target dynamic states.

4.2.2. Optimization method

Broadly speaking, two types of optimization methods are available. Gradient methods use the gradient of the objective function (the error in relation to the target) against the design variables (the optimization parameters) to enable optimization. In stochastic methods, design variables are varied at a specific probability to produce a variety of figures that are potential optimum solutions, and the optimum solution is selected from among this group. The project discussed here used an evolution strategy, which is a type of stochastic method.

4.3. Results of Model Verification

Because results are affected by the measurement accuracy of the data used in the model calculations and the target data for comparison, it can be challenging in the verification of a model that uses actual vehicle data to determine whether a specific issue originates in the model or in the data. In addition, because the actual values of the tire parameters are unknown, quantitative verification of the results of parameter identification also represents a challenge.

Artificial target data was therefore created by constructing a vehicle model from body, suspension, steering, and aerodynamics models and the tire model, conducting a one-lap circuit simulation, and by adding noise corresponding to actual driving conditions to the obtained vehicle dynamics data. This artificial data was then used to verify the model. This method enabled issues of measurement accuracy to be set aside, and because the tire parameters that should be obtained as a result of parameter identification were already known, it was possible to verify the tire model and its parameter identification section.

Figure 19 shows a time series comparison of the average error in vehicle’s dynamic states (longitudinal force, lateral force, yaw moment) for one lap in the target data and the model, using a specific identification calculation. Because the evolution strategy is a type of stochastic method, the identification calculations have been conducted 10 times for the purposes of comparison. Error for all the results is approximately 1.2%, and as the time series graph shows, sufficient accuracy was obtained for the analysis of vehicle dynamics. However, despite the fact that the figure for error in vehicle’s dynamic states was largely identical in both sets of results, a phenomenon could be observed in which synchronized variations in multiple parameters were observed. The combination of different parameters to produce an identical output from the model is termed a modal characteristic, and is a phenomenon that is often observed in multi-parameter models. Increasing the diversity of the target data is an effective method of controlling the modal characteristic in analysis results, and this study provided insights into the degree of diversity necessary.

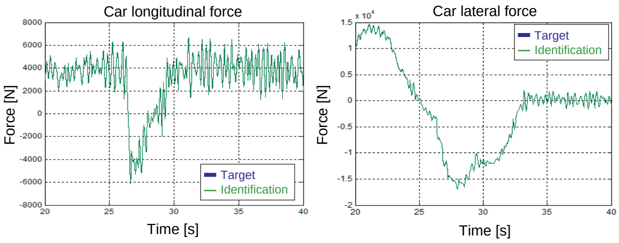

Fig. 19 Identification result (car dynamics error)

Based on the verification of the accuracy of the model described above, results for tire force and temperature were compared with results from track tests.

Figure 20 shows a comparison of measurements using a tire force meter and calculation results from the tire model for the fifth lap of five laps around the Barcelona circuit. The parameters for the tire model were identified using data from the third lap. Side force is calculated accurately across the entire range. Calculation results for the peak value of longitudinal force during braking are somewhat low, but results for turn-in correspond well. The slip ratio, one of the input parameters for the model, changes rapidly when the vehicle is braking, and it is therefore not easy to be confident of its accuracy. The effect of error due to input data accuracy was therefore considered to be greater in producing this result than the effect of the accuracy of the model.

Figure 21 shows a comparison of measurements and model calculation results for the temperature of the tire surface and bulk layers. During the period shown, the vehicle makes a pit stop (t=220 sec), and then reenters the track (t=280 sec). The model was able to reproduce the drop in the internal temperature of the tire due to the cessation of internal heat generation and the increase in the temperature of the tire surface due to the decline in heat dissipation into the air after stopping, in addition

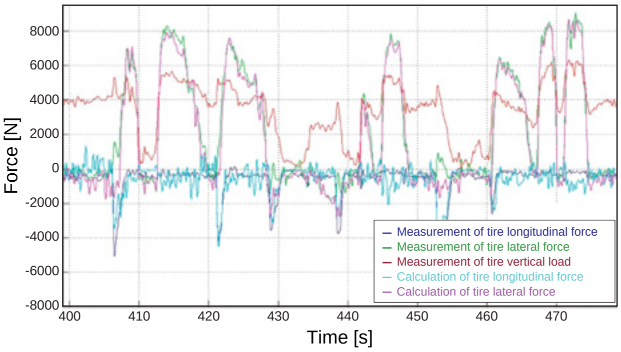

Fig. 20 Comparison of tire forces (front)

to the gradual increase in temperature until a state of thermal equilibrium is reached after the vehicle starts moving again. The model calculated the internal temperature of the tire at a somewhat high level during lap driving, but the level of accuracy can be considered sufficient for evaluating warm-up performance.

4.4. Summary of Tire Model Development

The project discussed in this paper developed a tire model that is able to perform coupled calculations of tire force and tire temperature that affects tire force. The use of a model configuration, in which parameter identification was performed for elements affected by driving conditions based on track data, enabled the realization of a level of calculation accuracy and speed satisfying a broad range of demands, from vehicle design to vehicle setup.

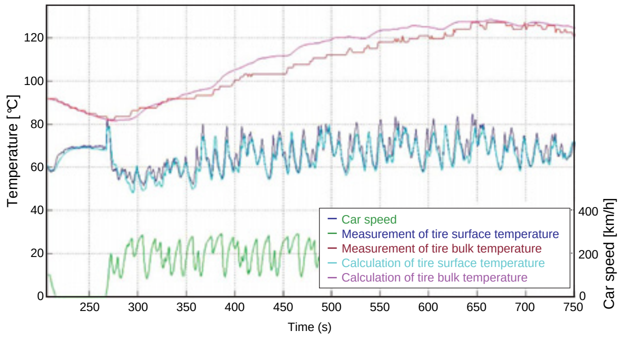

Fig. 21 Comparison of tire temperatures (rear)

5. Conclusion

As demonstrated by the technology introduced in this paper, vehicle dynamics simulation technologies play a significant role in developments relating to the dynamic performance of Formula One vehicles. In addition to the benefits of simulations in reducing costs and increasing development efficiency, the very process of observing phenomena, analyzing their mechanisms, and formulating models to develop a simulation technology in itself leads to dramatic enhancements in dynamic performance.

More recent developments, seeking further performance increases and enhancements in development efficiency, are progressing to the development and use of a driving simulator, which represents an evolution of vehicle dynamics simulation technology. The removal of the various external factors associated with track tests on a circuit enabled high quality test results to be obtained. The driving simulator was applied not only in evaluating the performance of development items, but also in the formulation of vehicle development concepts and the creation of indices for drive feeling in relation to dynamic performance. It is expected that these technologies will be actively employed in the development of mass production vehicles.

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