
Explanation of Honda's Third Era Formula One Engine Development

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ABSTRACT

During the third era Formula One engine development, as a measure for increasing the engine power through an increase of engine speed, the enhancement of the induction static efficiency and weight reduction of the moving parts was focused on. From 2007, restrictions on the maximum engine speed and development of the engine except for the induction and exhaust system were introduced. Therefore, the focus of the development changed to practical use of dynamic effect of induction and exhaust pressure. Moreover, the driver-aids including traction control was banned in 2008, so attention moved to the development with the objective of shortening lap times, and including drivability enhancements.

Also, to comply with new regulations concerning the longer use of engines, the restriction of use of materials, and to respond to changes in actual usage in circuit running in accordance with the change of regulations, the subdivision of the endurance mode and results feedback was performed, which achieved durable reliability in parallel with performance enhancement.

This document describes the evolution of the engine as outlined above, and includes descriptions of technology such as the lap time evaluation method and tools.

1. Introduction

Honda's third era Formula One activities began in 2000, with Honda competing with the other constructors to develop engines with higher engine speed and output. In 2006, immediately before the International Automobile Federation (FIA) introduced the engine speed restrictions, some competitors had achieved a maximum engine speed of 20000 rpm. At that time, the maximum engine speed that Honda had reached in a race was 19600 rpm.

In order to competitively increase engine speed, technology was required for reducing the reciprocating mass of the valve train system and the reciprocating system. To achieve this, in addition to developing materials and manufacturing technology, predictive computer aided engineering (CAE) was introduced for each part. In particular, a system had been firmly established by 2003 for designers themselves to produce 3D models and perform CAE analysis, enabling design that is optimized for structural strength, resonance, flow rate, temperature distribution, thermal stress and other factors to be performed in a short period of time. Induction potential was also required to increase engine power. To achieve this, a higher peak power engine speed was required, and technology that increases

induction efficiency was focused on.

Because friction and vibration increase quadratically with the rise in engine speed, attention was also given to technology that reduces mechanical loss, and to dealing with a vibration acceleration that reached 300 G.

Engine failure on the circuit may cause immediate retirement from the race, so high reliability was also required. The load on the engine was estimated for each circuit from the throttle opening angles and the duration of continuous wide open throttle (WOT), a driving mode suitable for the load was formulated, and then an endurance test on a test bed was performed.

From this, operating conditions for the race such as the temperature of oil and water and the individual ignition timing for each cylinder were established in advance, and measures were taken to help ensure high performance and reliability, and make one engine last for two races.

In 2007, the FIA restricted the maximum engine speed to 19000 rpm, and at the same time enforced a freezing of development of the main engine parts (homologation).

After that, attention moved to output characteristics that would shorten lap times, concentrating on the development of induction and exhaust system parts. Simulation tools for lap times and fuel efficiency were

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also developed for simulating circuit running conditions on dyno.

In 2008, the use of a common ECU was made compulsory and traction control was banned. This gave rise to issues of drivability when coming out of corners. Work was started on enhancing drivability by modifying the engine hardware, but as of 2009, this development issue remains.

2. Power

2.1. Era of High Engine Speed and High Output (2000 to 2006)

2.1.1 Increased engine speed and enhanced induction performance

If P_{se} : Shaft output, P_{mi} : Mean effective pressure, V_s : Stroke displacement, N_e : Engine speed, P_{sf} : Friction, then: $P_{se} = (P_{mi} \times V_s \times N_e/2) - P_{sf}$.

Thus, an effective way to increase the power is to raise the engine speed, and Honda competed with the other teams in increasing the engine speed and power.

Figure 1 shows the trend for the maximum engine speed.

Honda's V12 engines in 1992 had an engine speed of only 14400 rpm, but by the time the third era started in 2000, the level was 17000 rpm. Although the introduction of mileage extension regulations to make one engine last over one race event, and then two race events, slowed this growth, by 2006 it had still reached 20000 rpm in tests on dyno. However, for reasons of lap time contribution and engine durable reliability, an upper limit of 19600 rpm was set for the actual races.

When the target of the maximum power and engine speed are fixed, the power peak engine speed is determined from maximum engine speed, and the output value can be estimated as shown in Fig. 2. This means that the target output shortfall should be compensated for by reducing the friction and enhancing the combustion.

The induction performance target for the power peak engine speed was decided using a steady flow test, and development was performed of the cam profile and port layout, including the valve diameter, that was required for achieving the desired horsepower by controlling engine speed.

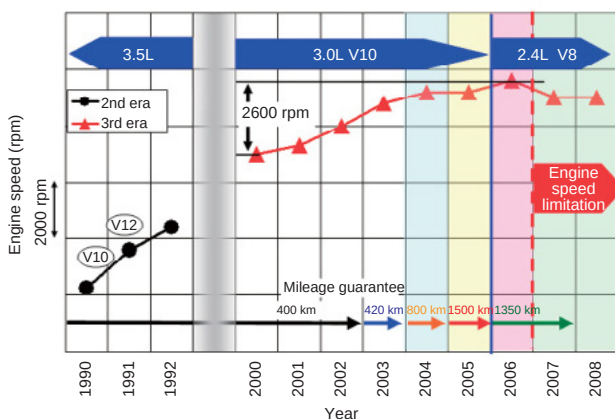


Fig. 1 Transition of max engine speed

The valve diameter size was decided from a good balance with the cylinder bore diameter, which was determined by also taking the piston speed into account.

The bore diameter started at 95 mm in 2000, but by 2002 it had been increased to 97 mm. In 2004, laser-clad welded valve seats were used in order to increase the valve diameter.

From 2000 to 2001, the tappet type was used for the valve train system, but because the valve lift was limited by the lifter bore, in 2002, the valve train system was changed to the rocker arm type in order to increase valve lift.

Cylinder head port development continued throughout the season, and over 10 types were evaluated. However, just because the induction performance was high in the steady flow test, this did not mean that the power would increase, and so development for enhancing the combustion, including fuel distribution, was required.

Immediately before the engine homologation in 2006, power had been increased by developing head port shape that maximized the dynamic effects, using not only the steady induction performance, but also 3D-2D coupled η_v simulation.

2.1.2. Making moving parts more lightweight for increasing the engine speed

With the increased engine speed, moving parts needed to be made more lightweight from the viewpoint of reducing friction and durable reliability. To make these parts more lightweight, materials with high specific stiffness and high-temperature fatigue strength were used, and their shapes were optimized using CAE.

In 2004, an aluminum Metal Matrix Composite (MMC) material with increased high-temperature fatigue strength was used for the piston, reducing it to a weight of 210 g at a size of ϕ 97.

After the engine mileage extension and the banning of MMC materials in 2006, the piston weight increased, but through CAE thermal stress analysis and with the enhancement of piston cooling using oil jets, a weight of 230 g was achieved using A2618 enhanced materials.

At the same time, reducing the shaft diameter was studied to minimize heat generation in the conrod bearing in the reciprocating system, and to achieve a good balance with stiffness, it was reduced to ϕ 34. Enhancements for durable reliability were also performed for the bearing itself, with a copper alloy with high thermal conductivity being used from 2005.

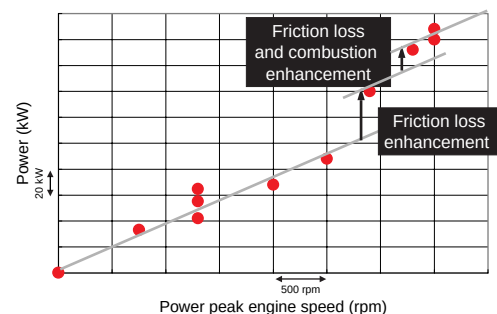


Fig. 2 V10 F1 engine power peak engine speed - power

The factors that were important in reducing the reciprocating mass of the valve train system were the use of rocker arms for the mechanism and the use of Titanium-Aluminide (TiAl) as the valve material. The reciprocating mass was reduced from 71.4 g in 2000 to 47.2 g. Even after the regulations on intermetallic compounds that were introduced in 2006, an equivalent reciprocating mass could be achieved with a titanium alloy using CAE analysis.

Figure 3 shows the positioning of the specific stiffness for the materials that were used in races. From the perspective of cost reduction, the specific stiffness was reduced to less than 40 GPa/g/cm³ in 2003, and in 2006, the use of MMC materials, intermetallic compounds, and magnesium alloys was banned. Regulations were also introduced for the main elements of the piston materials, allowing only conventional materials to be used.

2.1.3. Combustion

In Formula One engines that require higher engine speed and power, increasing the bore diameter is an effective method of enhancing the induction and exhaust performance.

However, increasing the bore diameter also increases the combustion duration, which leads to decreased thermal efficiency, power, resistance to misfiring, and the like. As a result, measures for making combustion faster were required. In the third era Formula One engine, the bore diameter was increased to ϕ 97, and combustion was enhanced to raise the compression ratio to 13.0. In 2003, a compound angle was added to the inlet valve to enhance the in-cylinder flow and make the combustion faster. Figure 4 shows the effects of shortening the main combustion duration.

2.1.4. Friction

When reducing the engine friction, a factor that had a particular effect was the friction in the valve train system. The behavior of the valves was enhanced by reducing the reciprocating mass and minimizing the angular velocity fluctuations, which reduced the spring load. In addition, the oil agitation resistance in the cylinder of the Pneumatic Valve Return System (PVRs)

was reduced. These measures reduced the valve drive system friction of 35 kW in the V10 engine to 12.8 kW by 2005.

Further studies were performed for reducing the agitation and shear resistance of oil, the sliding friction of the journal and reciprocating system, and the ancillary drive loss.

2.2. Power Curve Characteristics for Shortening Lap Times (from 2007)

2.2.1. Lap time simulation

In 2007, the development of new systems for the engine except for the induction and exhaust systems was frozen in order to reduce costs, and the parts that could be developed were limited to the air box, exhaust, and fuel systems.

After the maximum engine speed restriction was introduced, to maximize the team's competitive strength, the use of the maximum engine speed was extended to the 7th gear end of straight. Figure 5 shows the changes in engine speed for each gear level, while Fig. 6 shows

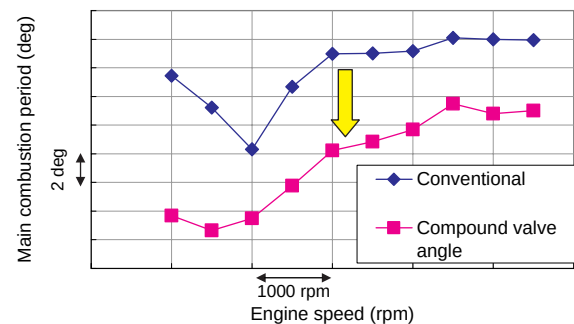


Fig. 4 Effect of compound inlet valve angle

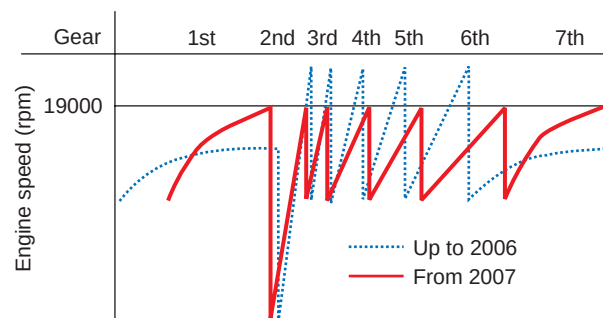


Fig. 5 Change of engine speed usage

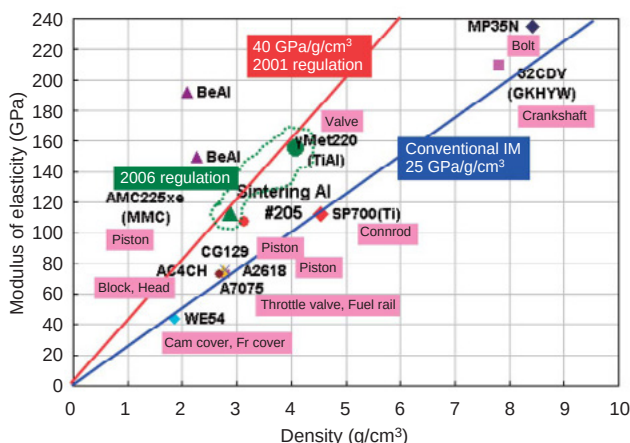


Fig. 3 Comparative rigidity of race engine materials

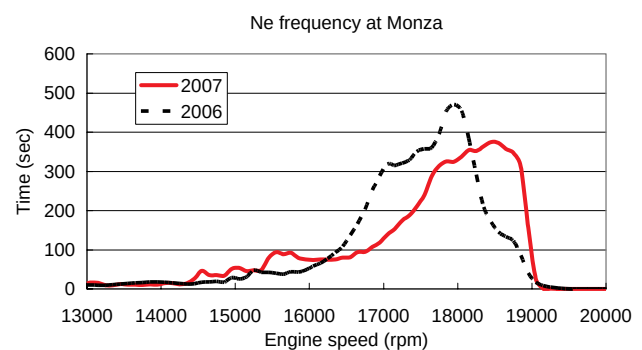


Fig. 6 Ne frequency difference due to maximum engine speed restriction

the engine speed frequency.

Figure 7 shows a comparison of lap times when the end of straight engine speed is 18500 rpm and 19000 rpm. It can be seen that at every circuit, the higher the end of straight engine speed, the shorter the lap times.

Figure 8 shows the effect of the power peak output engine speed on the lap time and maximum speed at the Shanghai circuit. It can be seen that the best lap time is at 18200 rpm, and that the time drops sharply with engine speeds below this level.

The shift-up engine speed, end of straight engine speed control (EOS) settings and gear ratios were optimized for each Formula One circuit to shorten the lap times.

Also, it became possible to theoretically calculate how the power curve characteristics would affect the lap times, and the calculation results were reflected in the development.

For the Monza circuit, with the power curve characteristics shown in Fig. 9, even though the power curve characteristics of Curve B is 12 kW less at the horsepower peak, the lap time was shortened by 0.04 seconds.

In the development, the lap time calculation was performed before the race was held in order to optimize the power curve characteristics.

2.2.2. Drivability

In 2008, the use of a common ECU was made compulsory, and driver aids were banned. In the engine, attention was focused on the fact that the banning of traction control and restrictions on control resulting from the common ECU affected lap times because of issues of drivability (abbreviated here to "DR") when coming out of corners. Figure 10 shows two DR issues: (a) the initial torque following at 8000 rpm, and (b) the torque hole generated by misfiring as the air-fuel ratio becomes

richer from 11000 to 12000 rpm.

It was thought that this decrease in DR would lead to a drop in the lap time of about 0.2 seconds.

Regarding these DR issues, for issue (a), spit-back was reduced by the early closure of the inlet valve and fuel sticking to the port wall was enhanced by changing the injector form to a beam. For issue (b), the amount of residual gas in the cylinder was reduced by tuning the exhaust, and the torque characteristics were enhanced by the early closure of the inlet valve. These addressed the issues of torque following and inconsistent combustion, reduced the disturbance from transient throttle operations, and enhanced the DR.

2.3. Engine Oil and Fuel Development

2.3.1. Engine oil development

Engine oil development was important in order to reduce friction and achieve durable reliability. Joint development was performed with Nippon Oil Corporation.

The power can be increased by lowering the base oil viscosity and the HTHS viscosity, but lower viscosity results in decreased durable reliability. As such, selecting the base oil and developing oil additives suitable for the parts and coating materials were performed continuously. Oil deterioration was not an issue because the replacement intervals were short.

2.3.2. Fuel development

The number of regulations, including for distillation characteristics, has increased since 1995, eliminating the prospect of increasing the output through fuel development. This situation continued for fuel

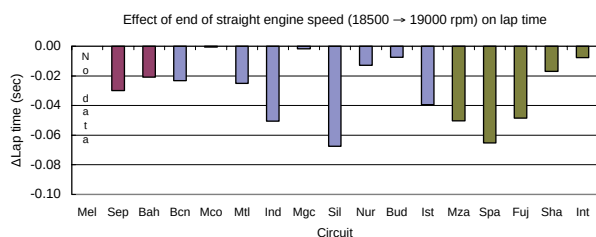


Fig. 7 End of straight Ne - lap time

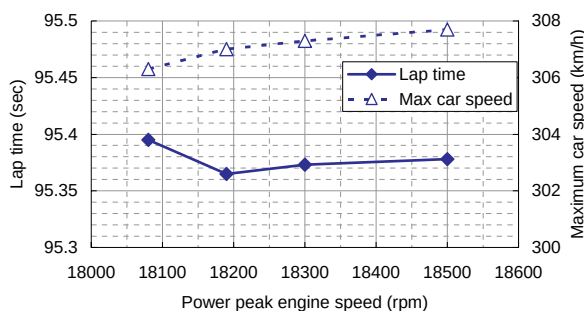


Fig. 8 Pe peak Ne - lap time / Vmax

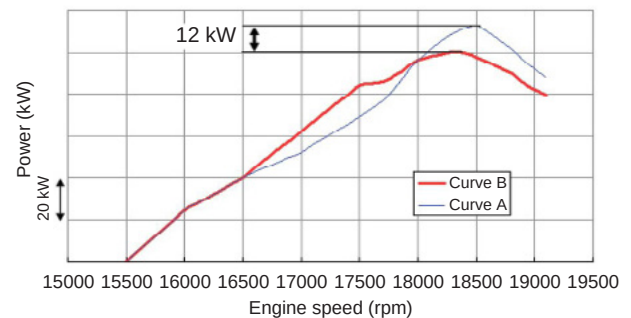


Fig. 9 Power curve shape comparison

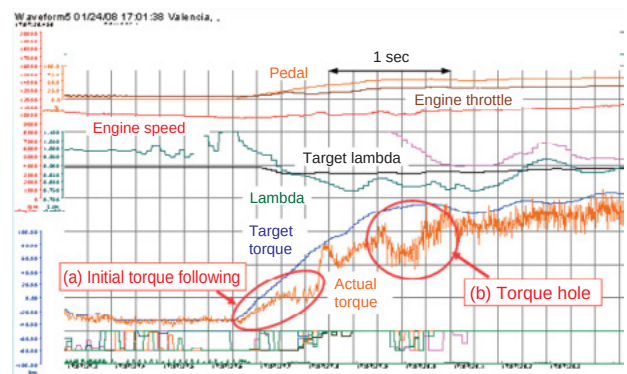


Fig. 10 Drivability issues

development in the third era of Formula One. From 2003, a small modification by mapping the fuel properties in line with the engine characteristics was performed, within the regulatory boundaries. In addition to power, specific gravity from the perspective of the fuel efficiency and fuel weight when the vehicle is filled with fuel were considered. Also, properties were studied that would be suitable for the atomization due to modified fuel pressure and injectors.

From 2008, the use of bio-gasoline (5.75% additive) became compulsory in Formula One, in consideration of environmental issues.

2.4. Achieved Power

Figure 11 shows the achieved power and power per liter for every year. The power increase trend became lower due to the engine mileage extension and engine development regulations, but even so, the power increased every year. By 2008, Honda had achieved a power increase of 23% over its level in its first year of participation in 2000.

3. Reliability

3.1. Guaranteed Endurance Distance

In the third era Formula One, engine operation (use distance) has changed greatly since 2004 due to changes in the regulations. For this reason, each year a review was held of the guaranteed durable reliability distance for the engine. Descriptions of the specific regulations for each year are omitted here, but the required guaranteed distance for each session was determined from the previous year's results and the regulation changes, and was used in the endurance tests on dyno (Fig. 11).

3.2. Guaranteed Endurance Mode

In order to guarantee the Formula One engine durable reliability, an endurance test mode needed to be set. However, this could not be set only through engine operation (use distance); the loads of each circuit also had to be taken into account.

In the third era Formula One, loads were classified into 5 levels to guarantee durable reliability.

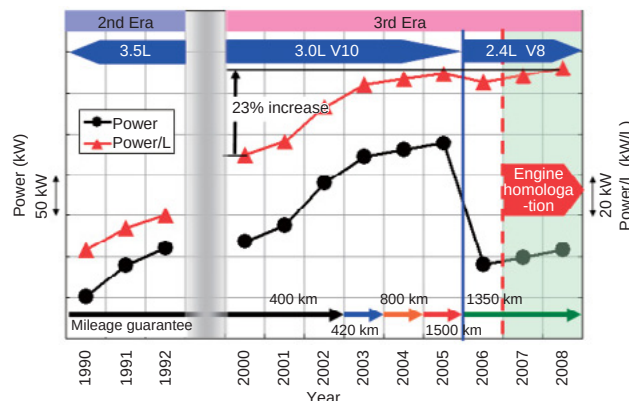


Fig. 11 F1 engine performance transition

Table 1 Endurance test loads classification

Load classification	Condition of wide open throttle		Typical circuits
	Frequency	Continuous time	
Minimum load	Less than 50%	Less than 10 sec	Monaco
Low load	Less than 70%	Less than 13 sec	Magnyours, Budapest
	70% and over	13 sec and over	
Medium load	Less than 70%	Less than 13 sec	Bahrain, Barcelona
	70% and over	16 sec and over	
High load	Less than 70%	16 sec and over	Istanbul, Fuji
	70% and over	16 sec and over	
Maximum load	70% and over	16 sec and over	Monza, Spa

Table 1 shows the load classifications (5 levels) in the endurance test. Up to 2004, the guaranteed durable reliability was evaluated with one endurance test mode for each load. However, from 2005 the regulation changed to one engine for two races, so the endurance test mode combined different loads to determine the guaranteed durable reliability.

Included in this, verification was performed on dyno for various operating conditions such as the temperature of oil and water, the individual ignition timing for each cylinder, the air-fuel ratio, the ignition cut and retard amount (T/C and O/C control) settings, shift cut during blipping, end of straight engine speed control (EOS), torque-drive, over-revving, idling, and the oil replacement timing, in order to maximize performance.

As a result of the endurance test described above, the engine speed frequency (Ne frequency) was calculated, and this was used as the reference for operating in the actual race. Figure 12 shows the representative Ne frequencies for the endurance test results and the race results.

With the increased engine mileage, the current method for confirming the guaranteed durable reliability takes a lot of man-hours and time. In the future, it will be necessary to take measures to guarantee durable reliability by using Miner's rule.

3.3. Reflecting the Endurance Test Results

After the endurance test on dyno and the end of the race, the changes in dimensions of various parts such as the tappet clearance, the wear amount of the piston clip groove, gudgeon pin hole diameter and connecting rod bearing, and the piston temperature were all measured. These were then progressively reflected in engine hardware studies and in operating condition settings such as the ignition timing settings and the engine oil

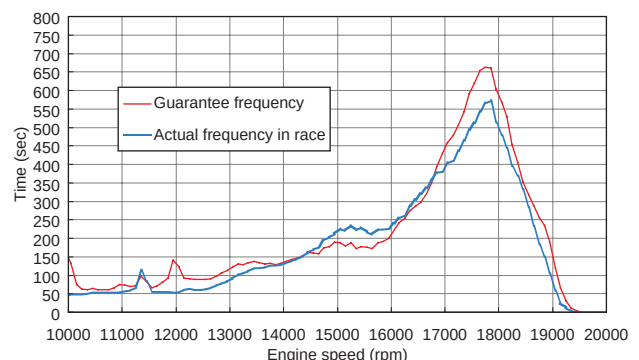


Fig. 12 Engine speed frequency (2006 Rd 17-18)

temperature control. Figure 13 shows the differences in the piston roof temperature in line with the cylinder bias (retard amount from the set ignition timing). It can be seen that by advancing the average ignition timing for all cylinders by 1.2 degrees, the roof temperature rises by about 10°C. Feedback was performed for these results, and the optimum balance for material strength was set for each circuit based on the power changes, cylinder pressure changes, and temperature changes that occurred due to the cylinder bias.

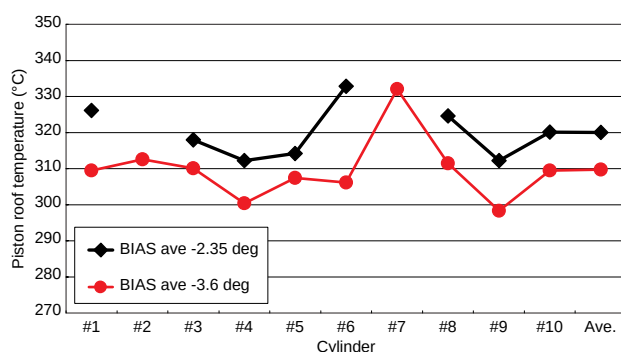


Fig. 13 Cylinder BIAS - Piston roof temperature

4. Conclusion

In the third era Formula One development from 2000 to 2008, high performance Formula One engines were developed that achieved high engine speed and high output, and durable reliability for one engine over two races, with the following results.

- (1) An increase in the specific output of more than 230 kW/L was achieved by increasing the engine speed, using the dynamic effects of the induction and exhaust pressure wave, enhancing the combustion, and reducing friction in various areas.
- (2) Circuit simulations were used to optimize the use of the power peak engine speed, shift-up engine speed, and end of straight engine speed for each circuit, and lap times were shortened. Also, knowledge was gained about the output characteristics for shortening the lap times.
- (3) Verification of various operating conditions was performed on dyno through the segmentation of the endurance evaluation mode, maximizing performance and providing durable reliability.
- (4) In response to regulations regarding material restrictions and extension of the use of engines, durable reliability was provided by using CAE technology and through the development of engine oil.

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