Development of Induction and Exhaust Systems for Third-Era Honda Formula One Engines

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ABSTRACT

Induction and exhaust systems determine the amount of air intake supplied to the engine, and as such are critical elements affecting engine output.

In addition, the layout of the induction and exhaust systems affects the vehicle's aerodynamic performance, and so it must be considered together with vehicle development.

At first, there were few CAE software and computer resources available, and induction and exhaust system components were produced by measurement and guesswork so that development was largely performed on a trial and error basis, but in recent years, the 3D-CAD and CAE software has advanced so quickly, and computer resources have expanded so much, that development is done by simulation.

The enhanced phenomenon elucidation and forecast precision have made it possible to shorten the time it takes to determine specifications and reduce development costs.

1. Introduction

The first thing required of a racing engine is power performance, but transient characteristics and vehicle package also impact performance. As shown in Fig. 1, the induction and exhaust systems are placed outside the engine, and have a large impact on the package.

Vehicle weight and inertia influence dynamic performance, but at a vehicle weight of 600 kg including the driver, the engine weight accounts for a large percentage of the total, so when designing engine components, one has to make them light while maintaining their necessary functions.

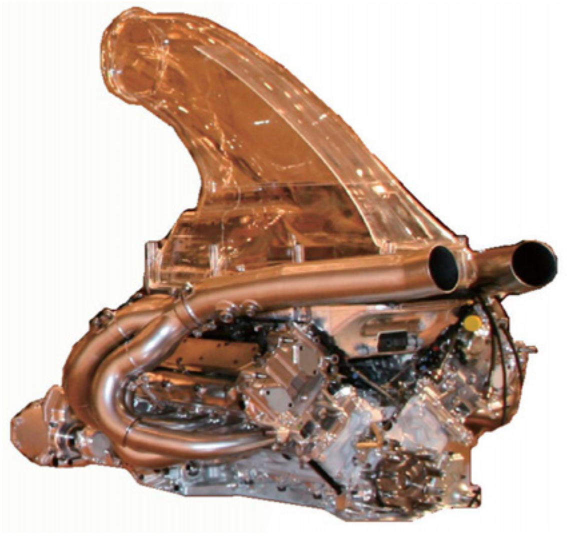

Fig. 1 Engine with complete induction and exhaust

The development of induction and exhaust systems was mainly about lowering flow resistance in 2000, when the initial development was being done, but since 2006, it has been possible to predict dynamic effects during the process of design examination, meaning that one can carry out optimal design, with consideration of vehicle package, in a short amount of time. This paper discusses the content of this development.

2. Induction

2.1. Induction System

2.1.1. Reducing flow resistance

One technique for increasing volumetric charging efficiency is to reduce induction system pressure loss (below, pressure loss). The main factors relating to pressure loss are air filter performance and airbox (below, ABX) form.

Sometimes impurities drift in when the ABX is opened after running, so an air filter is required to avoid having to retire from the race. Because it is located within the air intake passage, however, the filter's flow resistance directly affects intake resistance of the engine. Air filters, therefore, must be designed to reduce flow resistance.

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Honda's third-era Formula One engines originally used a sponge-type air filter from an overseas manufacturer, but in 2004 Honda began examining a nonwoven fabric-type air filter. In 2004 a Grand Prix event was held in Bahrain, in a dusty area, and the sponge-type filter was not able to trap the fine desert sand and presented the crew with a big challenge.

At first, they used a dry filter that was installed on mass-market vehicles in dusty areas. However, although this increased the scavenging ratio, pressure loss also increased and power dropped by 4 kW, so the use of this filter was limited to certain events.

Subsequently, an investigation was begun on how to achieve enhanced engine durability, reliability and a higher scavenging ratio without diminishing performance.

A wet, nonwoven fabric filter was developed with high scavenging ratio and low pressure loss, which was used starting with the Italian Grand Prix, one of the last events of the season.

Starting in 2006, engines were limited to eight cylinders, which led to frequent induction fires caused by backfiring. Similar phenomena were also seen in CART series V8 engines, along with the phenomenon of induction systems exploding and components scattering in CART races where premixed methanol fuel were used. In Formula One engines, the air filters suffered melting damage (Fig. 2), and simultaneously with this seeping into engines, CFRP components were burnt and vehicles left unable to run.

Engine controls were changed as a countermeasure, while the filter was changed to a highly fire-resistant material.

After that, there were no more troubles in actual driving from filters burning as a result of backfiring.

Because the flow resistance of an air filter is proportional to the square of flow velocity, it is important to evenly distribute and reduce the velocity of the air-flow through the filter in order to limit pressure loss.

Within the scope allowed by the layout and aerodynamic performance, one needs an efficient velocity transformation to the maximum filter area that fits inside the engine cover.

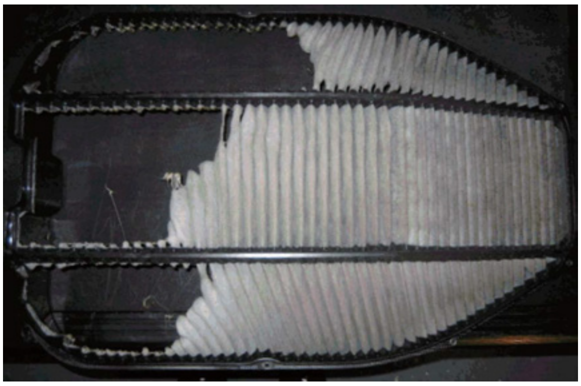


Fig. 2 Damaged air filter

Although it looks like nothing more than a container that simply supplies air to the engine, the ABX is an important component that takes air flowing at a relative speed of 300 km/h and turns it into a homogenous, low-speed flow of air to be sucked into the engine.

Figure 3 illustrates results of ABX CFD examination in 2008.

To reduce flow velocity in a limited package, one has to efficiently expand the air passage in cross-section. The velocity of air taken into the ABX contains a large horizontal constituent.

The layout of the ABX in the vehicle is such that the aperture is high to protect the driver, the ABX is front-mounted on the engine to concentrate the mass, and there are surfaces with much curvature in the front. These front surfaces are subject to separation, which causes variance in the amount of specific intake air volume to each cylinder and a drop in performance. Therefore, the form was optimized using CFD to enhance filter efficiency.

At first, the ABX was developed on the assumption that air is brought in to the ABX inlet homogenously. But a wind-speed simulator (below, WSS)(1) implemented in 2007 was used to simulate actual driving conditions and measured pressure distribution on the inlet duct. This made it clear that the distribution was not homogenous, as illustrated in Fig. 4. The results confirmed that engine power under these circumstances showed a 5 kW power loss as compared to a homogenous condition.

Figure 5 shows CFD results at low vehicle speed. The flow that stagnated at the lower end of the roll hoop rises while containing a Z-direction constituent up to a point close to the air intake and comes flowing into the

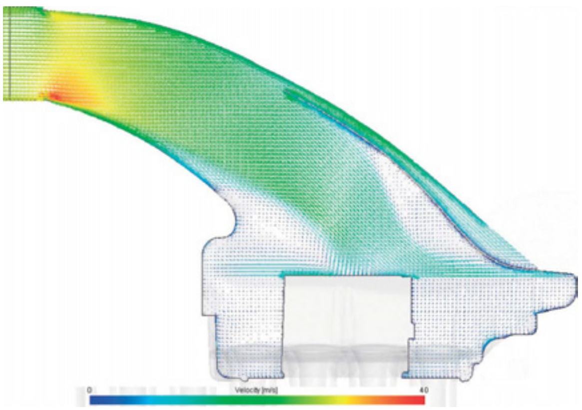


Fig. 3 ABX CFD result

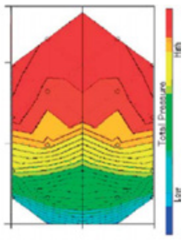


Fig. 4 Total pressure distribution at inlet to ABX

ABX. As a result, separation occurs on the lower surface of the part where the ABX comes in (below, the snorkel).

During development of the 2009 model, the air-flow status of the ABX aperture was considered during examination of vehicle aerodynamics, and development went forward using CFD to make inlet pressure distribution almost uniform.

2.1.2. Using intake pulsation

In an induction system, the intake pulsation caused by the opening and closing of the intake valve interacts dynamically within individual cylinders, among cylinders and between the cylinder banks. By controlling these interactions, one can try to enhance engine performance.

Figure 6 illustrates a variable-length intake system (below, VIS).

A VIS uses the fact that the intake pipe length has a dominant effect on engine speeds at which resonant supercharging effect can be achieved. By using this system, intake pipe lengths are continuously achieved that are appropriate for each engine speed. In addition, corrections are made that correspond to changes in intake temperature.

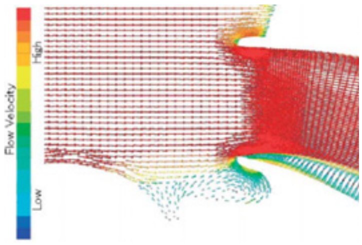


Fig. 5 CFD result of ABX inlet on chassis (150 kph)

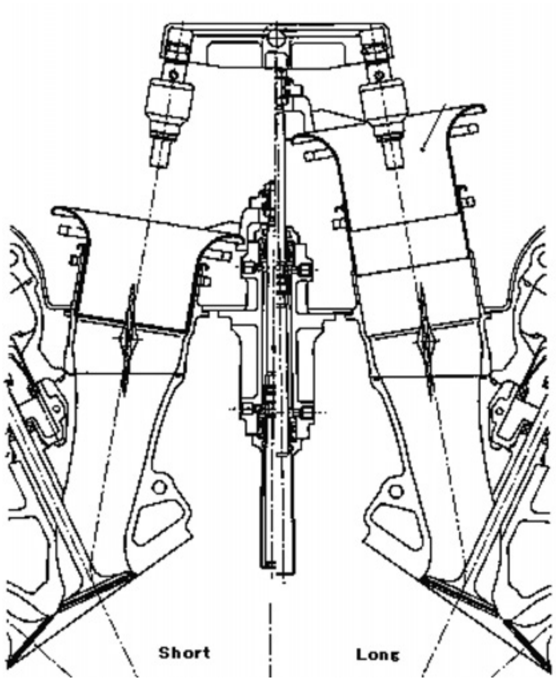


Fig. 6 Schematic view of VIS system

In a V10 engine, intake interference between the banks causes the quadratic standing waves in the ABX to amplify, with the result that the secondary constituent of the pulsation in the port attenuates, interfering with dynamic air intake.

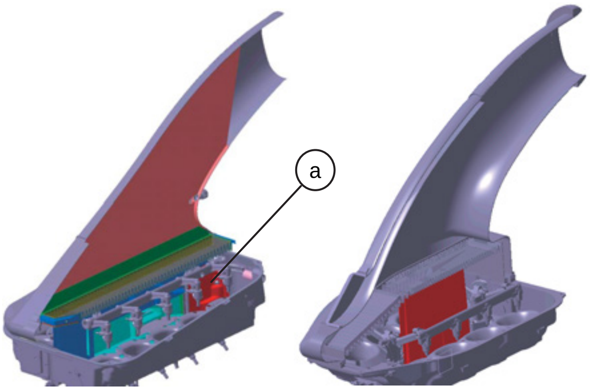
A splitter is an effective way to block interference between the banks. Figure 7(i) shows a splitter on the 2004 (V10) ABX. Adding on the splitter helped enhance power by 7 kW.

The item indicated by the letter “a” in the figure is a component installed to plug the small gap, which boosted power by 2 kW. However, because of the tolerance of this component and the variance that occurred when it was installed, the gap could not be completely plugged, and eliminating the impact the gap had on power was a continuing issue.

Fig. 7(ii) shows the splitter used since 2006.

The changes made to the regulations in 2006 required the use of V8 engines. In addition, the previously described VIS could no longer be used, so the team was required to expand the torque band with a fixed intake pipe length.

The effect of inter-cylinder interference within the induction system in a V8 engine is greater than that in a V10 engine (Fig. 8), and torque characteristics change depending on the form of the induction system. Because of this, inter-bank interference of the four cylinders in the center was controlled, while promoting active interference in the four cylinders in front and back,



(i) 2004 ABX splitter (ii) Local splitter for V8

Fig. 7 Schematic view of ABX splitter

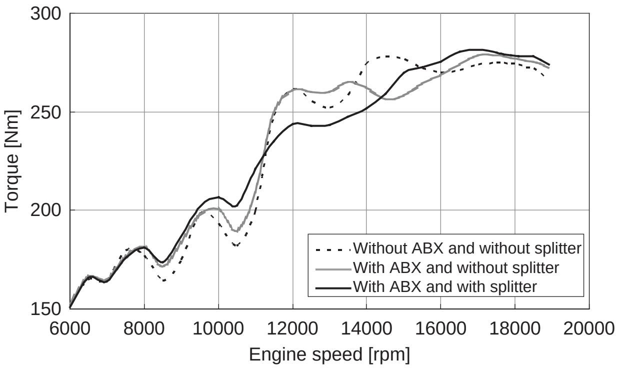


Fig. 8 Effect of splitters

which increases volumetric charging efficiency (below, ηv) over a wide range of engine speeds and flattens torque characteristics.

Figure 9 shows a test ABX for adjusting intake pulsation. Inserts made by a rapid prototyping machine are attached to and used on the interior of an ABX built to a large size. The ABX is made with lightweight CFRP to ensure rigidity in those areas where the inserts are attached.

The form-selection process switched to testing with the above test ABX, which made it possible to find the correlation between ABX wall form and power characteristics in a short amount of time. They were also able to be validated on 3Dηv simulation(2).

Examination of the making of inserts by rapid prototyping machine can be done until just before the test, and furthermore, the replacement with an optional part taking account of test results could be performed quickly.

Also, correlation with 3Dηv simulation was conducted simultaneously, with enough precision to forecast the power-performance benefit at the design stage.

2.1.3. Reduction of intake temperature

Reducing intake temperature is one technique for increasing specific intake air volume.

In a Formula One engine, the injector is located in the upper part of the intake pipe inside the ABX, and the fuel’s latent heat of vaporization is used to reduce intake temperature.

The injector height and angle are adjusted to maximize this effect.

In addition, a great distance from the inlet valve seat face enhances the temperature reduction benefit, but also leads to decreased engine response and drivability, so these considerations must be balanced.

It has been confirmed that intake temperature is higher than ambient temperature, and that the temperature difference between an air intake sensor located in the induction system and one in the nose is approximately 4°C. However, it was found that the actual intake temperature difference can be more than 4°C, depending on the peak brake power revolution as measured from drive-shaft torque in driving status. The reason for this can be speculated to be due to heating of the induction system by the increased temperature inside the engine cover.

As a countermeasure to this, engine control mapping was revised with the aim of enhancing reliability, while using the sensor in the nose as a reference point.

In addition, an air inlet was added to the engine cover to allow fresh-air induction (Fig. 10), and circuit tests were thus conducted.

Because the engine cover has a high flow rate on the surface and a high internal pressure, a reverse flow of hot air from within the engine cover occurs if unmodified. It was not possible to take countermeasures in 2008. In the design of the 2009 vehicle, however, this item was incorporated from the start, and a design was chosen that suppressed this temperature increase inside the engine cover.

2.2. Inlet Port

Points to watch in the design of inlet ports include:

- Charging stroke
- Fuel distribution
- Suctorial dynamic effect

Charging stroke and suctorial dynamic effect impact the absolute air-flow rate, while fuel distribution and flow-velocity distribution impact combustion speed.

2.2.1. Reducing charging stroke

In cylinder head design, the following are done from the time of layout to reduce charging stroke.

- Reducing valve stem diameter
- Adjusting valve form
- Adjusting valve layout
- Adjusting form close to valve seat
- Smoothing-out component surface on inlet port
- Adjusting port form

The valve head shape contributes to reducing flow resistance.

The valve margin thickness and angle R close to the valve seat face are adjusted, and a thin form of valve margin thickness is used as the final form.

As the valve lifts, the effective area expands. If at this time the distance between the cylinder wall and valve face is short, the effective aperture between the valve and seat cannot be used efficiently. Therefore, the valve pitch was decided by taking into account the valve face’s position relative to the cylinder wall.

In addition, the exhaust valve face was set in a

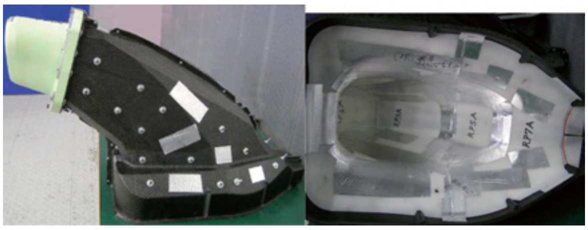


Fig. 9 Picture of test ABX and inserts

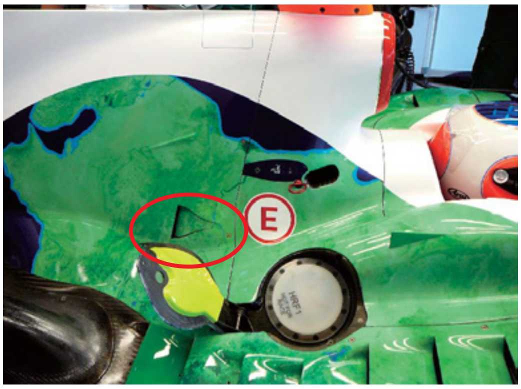


Fig. 10 Additional air inlet on engine cover

position so that it would not interfere with air inducted through the inlet.

The valve angle is one factor determining cylinder head size. For the 2005 Formula One engine, the valve angle was made small, and it was the most lightweight of all Honda Formula One V10 engines.

However, engines with small valve angles cannot get enough effective area relative to valve lift, which makes it difficult to increase power even if one does achieve a compact combustion chamber.

The engine in the first half of 2006 took the design of the 2005 engine into account, and the valve placement emulated that engine's as well, but power could not be increased for the above reasons, so the valve layout was changed mid-season.

Experiments were done with changing to a valve angle equivalent to that of 2004, but the ability to install to the chassis for racing was a necessary condition for making a layout change mid-season, so in fact, the finalized specification was intermediate between 2004 and 2005.

Because of homologation, which froze development of engines themselves after 2007, the valve layout was maintained as is.

A compound valve layout is a technique to achieve the compact combustion chambers needed to produce good combustion.

In a parallel valve layout, because port form and flow direction are arranged in relative conformity to each other, it requires no great effort to set a port form immediately over the seat. During the initial examination of the compound valve layout, the seat's upstream form was mapped together with the valves in parallel, and the effective area relative to the parallel valve port used as a base was reduced. However, because the actual flow showed no direct correlation to the valve stem (Fig. 11), the form was designed with no consideration for the valve stem, thereby minimizing the loss in effective area. As a result, power was increased by 4 - 6 kW, including the valvetrain design.

In designing the port form, one chooses a form that tries to control the separation that occurs on the side towards the lower face inside the port (a). As for the form of the upper face close to the seat, designers are conscious of overall air flow. Since the master stream of air flows in a different direction from that of the valve stem, the part directly over the seat (b) is not expanded (Fig. 12).

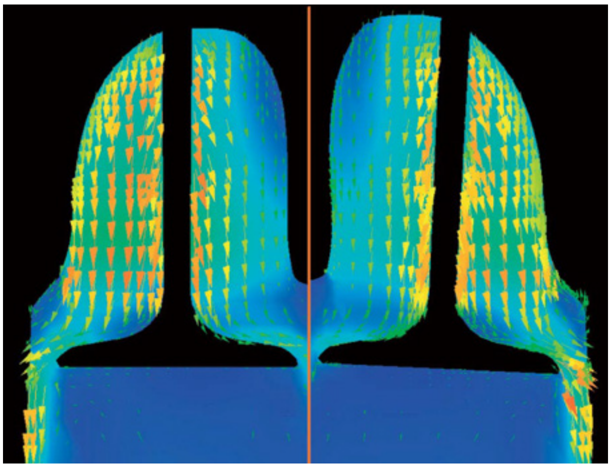


Fig. 11 Influence of shape around valve seat (Left : Parallel Valve Right : Compound valve)

2.2.2. Fuel distribution

In the early stages of engine development in 2000, the main focus was on reducing intake resistance. During development in 2004, a port to control separation from the inner face was examined as a technique to reduce intake resistance. Expansion of port volume was approved and ηv was expected to increase, but power actually went down. The discrepancy expected in the measured ηv could not be identified, and it was considered that perhaps some factor other than mass flow-rate was impacting power performance. It is considered that, although this specification controls separation, there is significant fuel adhering to the internal wall as a consequence. Figure 13 shows results of a check of fuel adhering to the port internal wall. Where the color is darker in the figure, fuel is adhering to the internal wall of the port. It can be confirmed that ports with reduced intake resistance have more fuel adherence.

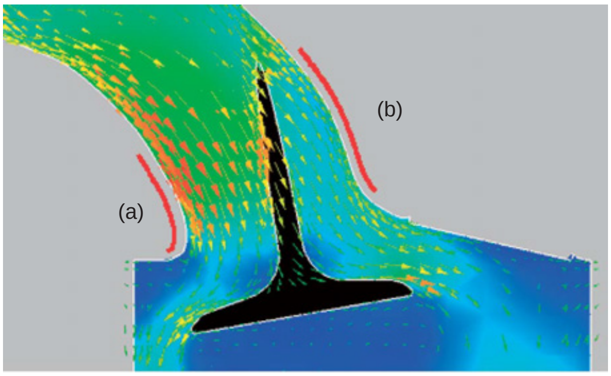


Fig. 12 CFD result of 2004 inlet port

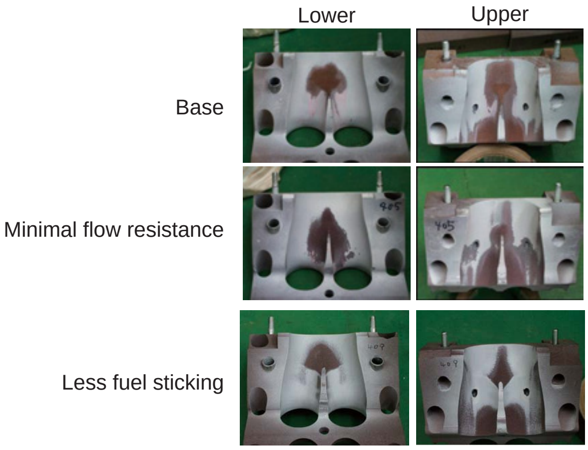


Fig. 13 Fuel sticking area with inlet port when conscious of flow (middle)

By controlling fuel adherence, a power increase of 2 kW was achieved. It was confirmed that besides reducing intake resistance, the volume of the inlet port and volume allocation in sectional area also affect power. It was simultaneously confirmed that the form of the port is also related to the form of gas mixture in the cylinder.

2.2.3. Dynamic effect

Following on the fact that ηv does not increase in enlarged ports with reduced flow resistance, in the middle of the 2004 season an investigation was initiated into forms that would narrow-down the inlet port within the range where flow resistance would not be decreased. This concept accounted for 3 - 6 kW of power gain and was used in the 2004 Japanese Grand Prix. Since then, Honda models up to 2008 were given similar distribution in sectional area.

Analysis testing with a single-cylinder engine was done to accelerate port development. However, in comparisons of Formula One engine port performance, multi-cylinder engines (V8 with intake interference) and single-cylinder engines (with no intake interference) have sometimes shown completely opposite trends (Fig. 14).

The cause of this is intake interference between cylinders in a V8 engine. Two approaches can be taken as countermeasures: controlling intake interference with the ABX; and optimizing ports in places where there is intake interference.

During development of the 2009 engine, the inlet port form was examined with the objective of promoting flow within cylinders (tumbling). Although there was a trend for the effective area to grow smaller, no difference was found in performance, and no great discrepancy was found in ηv at this time. These results could not be explained just from the perspective of reducing charging stroke.

2.2.4. Inlet port development techniques

When designing an engine, the platform is first decided, then the form of the ports included in this platform is designed, and finally the induction system is designed.

However, advances in 3D CAD and CFD have now made it possible to predict induction system performance with high precision at the design stage. It is therefore possible to design an optimized induction system at the earliest stages of development, and overall performance of the induction system as a whole as well as development efficiency have been enhanced.

To increase efficiency of inlet port development, the method of filling ports with adhesives and again applying CNC processing techniques was adopted in 2004. This offered the advantages of being able to produce optional parts in a short time so they could be put into use more quickly, and of being able to minimize the effect of individual differences on engine performance.

3. Exhaust System

3.1. Exhaust Port

During the study of single-cylinder engines, it was learned that flow rates from exhaust ports rose to nearly the speed of sound and caused choking. In steady flow tests, the flow velocity did not come close to the speed of sound due to equipment capacity, and thus choking was not recognized.

While in choke, flow depends on cross-sectional area and the state of the fluid, so performance tests were conducted after expanding the part with the smallest cross-sectional area. Some enhancement of performance was seen with the single-cylinder engine, but none was observed in the V8 engine. In a single-cylinder engine, choking occurs during the period of valve overlap from blowdown, but in the V8 engine, there is a range where pressure within the exhaust pipe is high compared to that of a single-cylinder engine because of the effect of inter-cylinder interference, so it is believed that a high pressure differential such as would cause choking does not exist, so the same effect could not be achieved.

The cause of this is that, at exhaust-pipe diameters that would be realistic on board a vehicle, it is not possible to produce a diffuser effect that would cause choking of the throat of the exhaust port of a V8 engine, as shown in Fig. 15. However, by using expanding pipe that brings flow velocity close to the speed of sound within the exhaust port, staying within the range of equipment that can be mounted on board and without expanding port diameter, performance could be enhanced at high engine speeds.

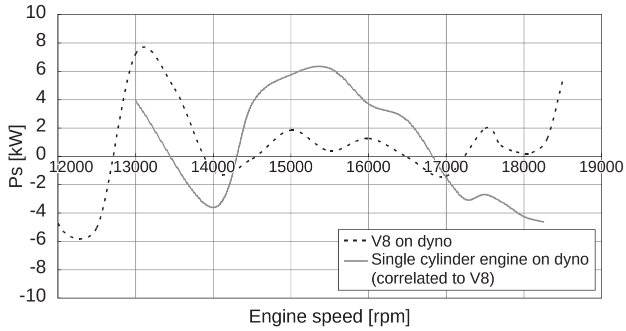


Fig. 14 ⊿Ps of inlet port on V8 and single cylinder engines

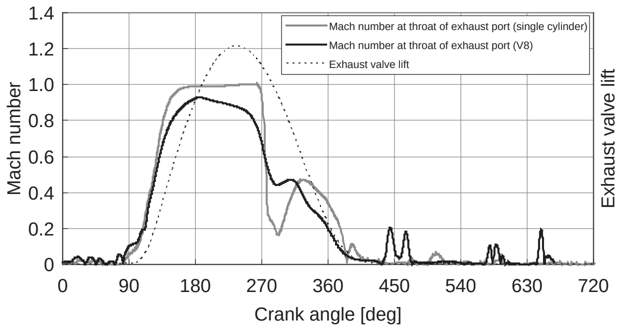


Fig. 15 Calculated mass flow of exhaust port

3.2. Exhaust System

3.2.1. System overview

The exhaust system of a Formula One engine consists of three parts: primaries, a collector and a tail. Figure 16 shows these in assembled form.

In exhaust systems used for testing on a dyno, the three components are each configured separately, which takes account of the need to change components because of damage, and the need for tuning between the collector and tail. In exhausts for actual vehicle testing and racing use, however, the collector and tail are welded together and are used as a single piece. Although making the three components into a single piece would make the exhaust lighter in weight, the primaries are kept separate to enable spark plug maintenance, during which the cylinder head covers are removed. The material used was Inconel 625, with pipe thickness of 0.7 mm.

In the world of Formula One, which is under no emissions regulations, the exhaust system is designed for high power. Broadly speaking, there are two points to focus on: reducing exhaust loss and using the dynamic effect of exhaust pulsation.

To reduce exhaust loss, pressure loss has been consistently reduced by enlarging the pipe bending-angle and bending-radius within the limits allowed for the layout under the vehicle cover (cowl).

On the other hand, the primaries are gathered together to utilize exhaust interference. As a result, within the collector, exhaust pressure causes reflected waves to form from the open edge. These reflected waves have an effect on internal pressure in the cylinders during valve overlap, and the amount of residual gas can be decreased. This leads to an increase in specific intake air volume as a result, making it possible to alter power characteristics in relation to engine speed. This uses the dynamic effect of exhaust pulsation. With the reflected waves in the collector alone, however, the range of engine speeds in which pulsation can be used is limited, so stepped pipes (steps) were implemented in the primaries (Fig. 17).

At 17500 rpm, a gain of 4 - 8 kW was realized as compared to an exhaust without steps.

While Honda was competing in Formula One during the third era, a forward exhaust system was used in 2007 only (Fig. 18), while a backward exhaust system was used in all other years (Fig. 19).

In order to enhance car aerodynamic performance to compensate for the engine power that decreased with the change in regulations that stipulated V8 engine use, it was necessary to increase the degree of freedom of aerodynamics design. A forward exhaust system has less negative impact on engine power than a backward exhaust system, and allows a greater degree of freedom in the aerodynamics design of the rear of the engine.

However, all the high-temperature parts were contained within the engine cowl, and the exhaust outlet was placed in a position that did not promote ventilation from the outlet, so there was frequently heat damage, including to vehicle parts. For that reason, Honda returned to the backward exhaust system in 2008.

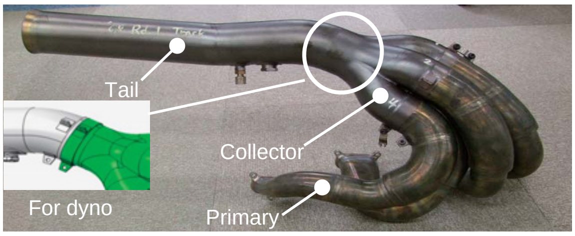


Fig. 16 F1 exhaust system (right-hand side for car)

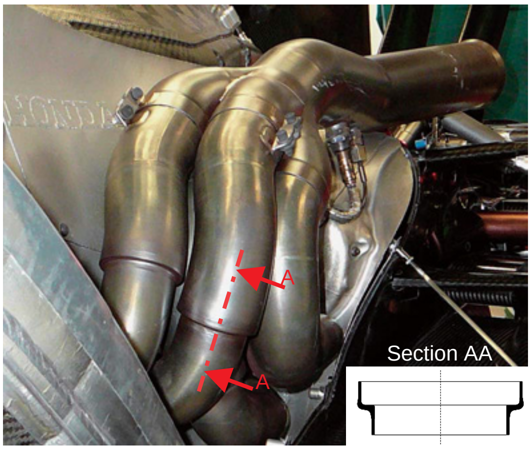


Fig. 17 Stepped primaries

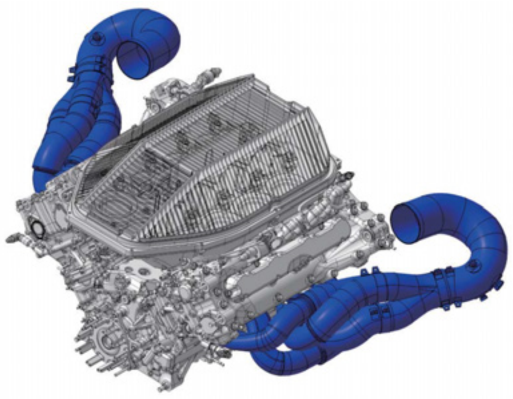


Fig. 18 Forward exhaust system

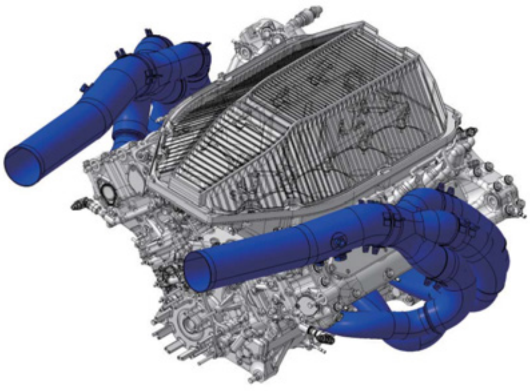


Fig. 19 Backward exhaust system

3.2.2. Compact and lightweight technology

The exhaust system has a major impact on a racing car’s vehicle dynamics in terms of component size and weight. Therefore, the technology of packaging the components themselves was always being advanced.

Because an exhaust system is made by bending cylindrical pipes, the primaries and collectors require space within the cowl and have an impact on aerodynamics.

With the exhaust system with non-circular sections (compact exhaust) developed in 2008, the aim was to achieve a space-saving, lightweight exhaust system that retained engine power, durability and reliability, rather than deciding on an exhaust form in a way that depends on the aerodynamics concept based on the cowl.

For the primaries, a non-circular section structure, three-dimensional bend layout and ellipsoidal stepped pipes were used and design was conducted that took account of heat damage to the engine itself. The production method proposal ensured molding accuracy by pressworking that took advantage of the know-how of an exhaust system manufacturer.

To make the collector lighter, it was considered to use a shared-pipe outer wall where the collectors gathered together, and to use a long collector in which a part of the primary would be taken into the collector and sharing of the wall further increased, and components were thus produced.

When sharing the pipe outer wall, if using pressworking, which is the conventional way, more dies are needed and material yield declines, which raises production costs, so a new precision casting technology was used. The result was a form with wall thickness of 0.7 mm (Fig. 20).

To deal with the increased thermal load that comes from sharing the pipe outer wall, René 41 was used, which is suitable for casting and has greater high-temperature fatigue strength than conventional materials. Results showed that in dyno durability tests, component life was extended about 60% over that of ordinary Inconel 625 collectors.

An image of the entire compact exhaust system is shown in Fig. 21.

These specifications allowed the cowl line to draw 50 mm closer to the engine than before. However, in order to make effective use of limited space while minimizing the impact of using a non-circular section, a layout was chosen that extended primaries to a length greater than standard specifications and wrapped them around to the engine front.

Figure 22 shows results of checking engine power under these specifications. This shows the compact exhaust power gain under the condition that the primaries have been extended. This is for a single bank, but there was an increase in power of 4 kW on average from 7500 rpm to 11500 rpm. The factor that increased power is believed to be that, since the volume of the collector gather was approximately 34% less than the conventional specifications, there were changes in exhaust pulsation in a certain engine speed range, which caused engine power characteristics to change.

3.2.3. Torque boosting technique

During races, engine speeds of 16000 rpm and higher are used about 90% of the time. However, torque characteristics at lower engine speeds are critical at the start of the race and when the car is accelerating from the apex of the curve, and such characteristics affect lap times and race results.

For that reason, the exhaust system is developed not only for power at high engine speeds but also for torque characteristics at low engine speeds. Specifically, the form of the internal wall of the collectors has undergone optimization since 2005.

Figure 23 shows a cross-sectional view of collectors with internal walls.

The form of the internal wall in a standard collector is decided by the collection angle of the pipes as well as the pipe diameter, and the wall edge forms a curve. If left unmodified, the cross-sectional area of the pipe would remain unchanged up to the gather as it went to the open edge.

If the wall height were intentionally raised and the cross-sectional area restricted, there would be no

Fig. 20 Casting collector

Fig. 21 Compact exhaust system

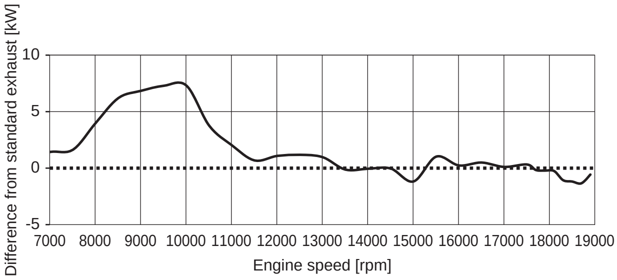


Fig. 22 Performance of compact exhaust system

decrease in power at high engine speeds as a result of increased pressure loss, and the phase of reflected waves would be delayed. This is thought to be caused by the fact that the distance to the open edge was increased and exhaust gases were kept below supersonic speed.

As a result, exhaust pulsation characteristics change at low engine speeds and combustion gas flow inside the cylinders is impacted, causing changes in torque characteristics. Starting in 2005, the optimization of the form of the internal wall of the collectors was constantly pursued as one means of enhancing torque characteristics at low engine speeds.

Since 2008, the regulations have prohibited the use of traction control systems, making it even more necessary to enhance torque characteristics from the point of view of drivability.

However, there are areas where optimization of wall form alone is not sufficient compensation, and there is also the effect of inconsistent combustion, so the issue of drivability was not completely resolved.

An effective way to enhance drivability is to flatten engine torque at partial throttle (i.e., engine torque when the throttle is neither fully closed nor fully open) at low engine speeds.

To increase development efficiency, a test exhaust system with variable pipe diameters and lengths was used (Fig. 24) as well as simulation to study form, thereby verifying the drivability enhancement effect. This part discusses two results that demonstrate the effectiveness of development.

The first was an exhaust system with connecting pipes (i.e., balance pipes) (Fig. 25). The goal was to cause changes in exhaust pulsation characteristics with these connecting pipes. Simulation was used to select connecting pipe width, length and connecting points, and specifications were selected that enabled residual gas to be reduced.

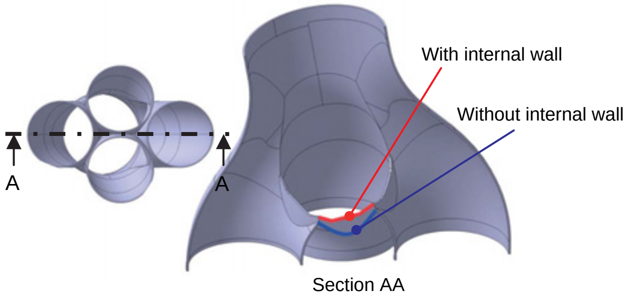


Fig. 23 Cross-sectional view of collector

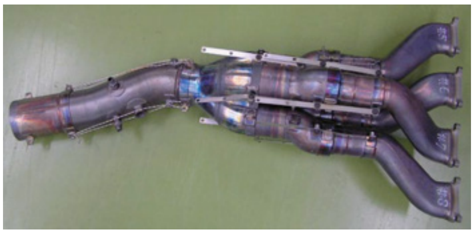


Fig. 24 Test exhaust system

The second was the 4-2-1 exhaust system. The basic stance was to alter exhaust pulsation characteristics just as for the balance pipes mentioned above. Specifications were selected while confirming the power with the test exhaust system. Ultimately, the primary length was made 50 mm longer than in a 4-1 exhaust system, with 360° assemblies of #1-#4, #2-#3, #5-#8 and #6-#7 (i.e., connecting cylinders with the ignition phase offset 360°).

Power check results are shown in Fig. 26.

The balance pipes yielded a power gain of 12 kW at engine speeds of 8500 rpm and 10500 rpm, but a drop of 2.5 kW at 17000 rpm.

The 4-2-1 exhaust system increased power by an average of 8 kW at engine speeds from 8500 rpm to 10500 rpm and yielded about the same results as the base exhaust (4-1 exhaust system) at 17000 rpm and up.

Figure 27 compares results of engine torque at partial throttle.

Both the balance pipes and 4-2-1 exhaust system showed torque flattening and superior performance as compared to the base exhaust.

Fig. 25 Balance pipes

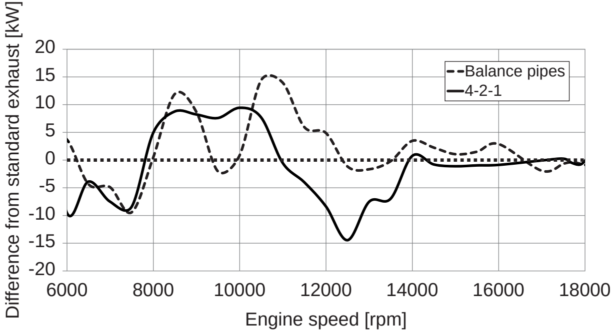


Fig. 26 Performance of balance pipes and 4-2-1

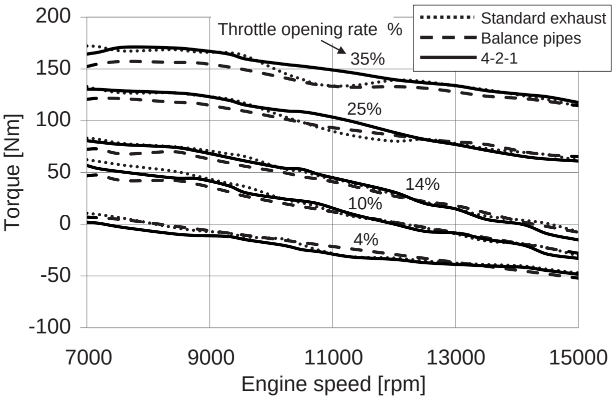


Fig. 27 Torque characteristics at partial throttle

However, drivers were not able to experience the superiority of the balanced pipes in circuit tests. Also, the connecting pipes caused the weight to increase, and there were still issues with durability and reliability because of scattered cracks in the weld to the base pipe.

It was estimated that the weight increase would be approximately 220 g over that of the base exhaust.

4. Conclusion

Through engine development during Honda’s third-era Formula One activities, we have learned the following about induction and exhaust systems.

(1) The importance of induction and exhaust system design that is mindful of the vehicle package became apparent once again, and development techniques were created that extract maximum performance from Formula One cars.

(2) Even with racing engines, it is necessary to be aware of torque characteristics at low and medium speeds, and is important to design exhaust systems as a technique for their enhancement.

(3) Induction system development techniques were created that use CFD and can predict dynamic characteristics from the design stage. If it is possible to predict the dynamic characteristics of exhaust systems in the future, this will enhance development efficiency even more.

(4) Test part-production techniques were implemented to suit a short development cycle, and the time required to optimize power characteristics and determine specifications was shortened.

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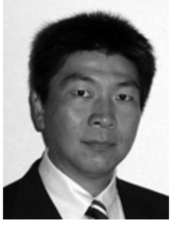

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