Development of Hybrid System for Formula One

Masataka YOSHIDA*　Masato KITA*　Hirofumi ATARASHI*

ABSTRACT

In 2009, the regulations for the Formula One World Championship were amended to allow the use of kinetic energy recovery systems (KERS). The new regulations stipulated that the KERS drive shaft be limited to the rear wheels, that output should be no more than 60 kW, and that the amount of energy used per lap be no more than 400 kJ. Honda had been conducting R&D in this area since the summer of 2007, and had developed a high speed, high output, direct oil-cooled motor, a water-cooled power control unit (PCU) which integrated a motor drive inverter unit and voltage control system, as well as a high power density lithium ion battery, all based on being small and lightweight enough for Formula One characteristics.

This system was first used to drive on straight roads in April 2008, and in May of that year Honda beat out other teams to conduct the world's first driving tests in an actual vehicle at the Silverstone Circuit, where the technology's superiority and high level of safety were proven.

1. Introduction

Honda has been developing electric vehicles, fuel cell electric vehicles and hybrid vehicles to find alternatives to fossil fuels, reduce emissions and mitigate the impact of automobiles on global warming.

As for the Formula One World Championship, the regulation amendments of 2009 allowed usage of KERS, which recovers and utilizes braking energy as drive power assist. To work with the new rules, Honda chose for its energy recovery method an electrical hybrid system and proceeded with development for use in Formula One based on the electric drive technology it had been developing.

Because the maximum output and the amount of assist energy that can be used per lap are stipulated by regulations, this development focused on making equipment as small and lightweight as possible with high output and high torque technology without changing the high level of dynamic performance unique to racing cars, and therefore Honda developed a motor, PCU and lithium ion battery capable of installation on a racing car. Honda additionally achieved high responsiveness to meet the requirement for output characteristics during racing.

Development began in earnest in the summer of 2007, and in just nine months, actual driving tests were conducted using the prototype vehicle RA1082 (a vehicle built to check functionality), and subsequently KERS was run at full power on a racing course for the first time in the Formula One environment. Based on the basic functions that had been confirmed with the RA1082, the technology then went into the RA1089 (race prototype) and then the RA109K (racing vehicle) by the end of 2008 (Table 1).

This paper recounts the development of the Formula One hybrid system.

2. Development Concept

Under the 2009 regulations, KERS could only be connected to the rear wheel, with maximum energy use per lap of 400 kJ and maximum output of 60 kW. The necessary performance targets set as development themes for this project were as listed below, not only to make the equipment compact and lightweight in order to be installed on a Formula One vehicle, but also to create a vehicle capable of winning races.

(1) System weight: no more than 30 kg
(i.e., no more than 60% of the vehicle ballast weight of the 2006 vehicle)

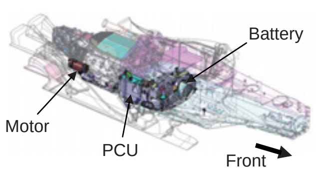
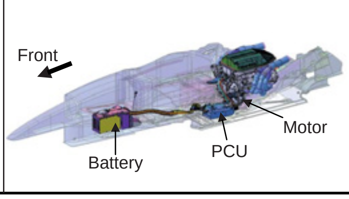
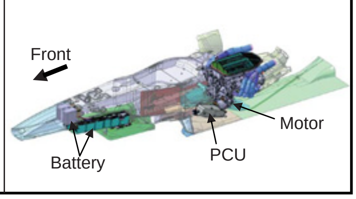
(2) Assist performance: at least 5 continuous seconds at output of 60 kW
(i.e., the output and assist time enabling the vehicle to overtake others)

When setting targets for performance, weight, center of gravity and the like for the various functional components, these parameters were investigated from many angles, including race strategy and the use of vehicle dynamics simulation, but some major concept-related issues were encountered when doing these investigations.

One was whether the race strategy should emphasize

* Automobile R&D Center

Table 1 Specifications of KERS

Vehicle code		RA1082	RA1089	RA109K
Shake-down		2008-APR	2008-NOV	2009-JAN
Motor	KERS power	60 kW	60 kW	60 kW
	Torque	45 Nm	45 Nm	45 Nm
	KERS energy	800 kJ	400 kJ	400 kJ
	Location	Transmission	Front of engine	Front of engine
	Dimension	ϕ100 x 202	ϕ100 x 190	ϕ100 x 190
	Max rpm	21000 rpm	21000 rpm	21000 rpm
	Weight	7.7 kg	6.9 kg	6.9 kg
	Cooling	Transmission oil	Engine oil	Engine oil
PCU	Power module	Si-IGBT/SiC-diode	Si-IGBT/SiC-diode	Si-IGBT/SiC-diode
	VCU type	Boost copper	Switched capacitor	Switched capacitor
	Operating voltage	680 V	560 V	580 V
	Weight	11.2 kg	8.0 kg	7.4 kg
	Cooling	Water	Water	Water
Battery	Type	Li-ion	Li-ion	Li-ion
	Cell number	114	108	106
	Weight	22.4 kg	21.2 kg	20.8 kg
	Cooling	Air	Air	Air
Layout				

overtaking or lap time. We compared single assist, which uses the 400 kJ all at once, or multi assist, which splits the maximum 400 kJ to use it on multiple instances; simulations showed that compared to single assist, a multi-assist system that settled the energy budget at each corner could reduce lap times by about 0.1 seconds. Figure 1 shows the time gain achieved on each circuit owing to the difference in type of assist. A multi-assist system allows smaller energy storage, so installation of a super capacitor with low energy capacity but great power density was considered. This would have the synergistic effect of having a lesser impact on the chassis. However, one cannot win a race unless one gets out ahead of other cars. For example, if assist is begun at 180 km/h, where the tire grip exceeds the drive torque (i.e., the tire is not skidding), assuming that the output of 60 kW will be used for 6.666 seconds (an energy equivalent of 400 kJ), vehicle speed can go 15 km/h faster than without assist, which in distance terms is a difference of 20 m. Even supposing that it were not possible to use assist for 6.666 seconds because of the course layout or other reasons, this would be a distance gain of 5 m (one car length) in 2.78 seconds and 10 m (two car lengths) in 4.22 seconds over another vehicle, which allows overtaking, so single assist, in this case, is more effective in terms of race strategy (Fig. 2). The opinions were thus divided on how to use KERS in actual races, so there was even some wavering on target requirements, but after several discussions with the Honda Racing Formula One Team (HRF1), the concept of emphasizing overtaking was ultimately decided upon.

The second issue was to maximize KERS's recovery of energy from braking while also maintaining drivability. Brake cooperative control, and the like is prohibited under the regulations, and therefore the amount of energy recovered varies not only according to course layout but also according to driving style, including such factors as how long and at what pressure

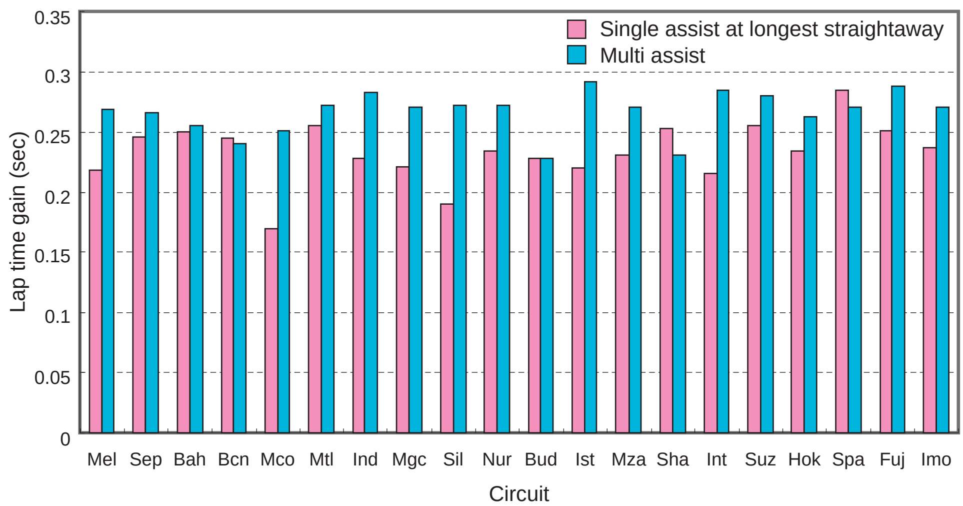


Fig. 1 Lap time reduction

the brake is operated. Additionally, simulations indicated that, depending on the circuit, it may not be possible to recover the target amount of energy. To address these issues and minimize the differences in driving style, we minimized loss from zero torque control that occurs during shift change and when offsetting motor friction, and furthermore achieved optimal allotment of engine braking and regenerative braking and made settings to let each functional component work with maximum efficiency in the range of usage. In order to get more regenerative energy, Honda also decided to propose to the Federation Internationale de l'Automobile (FIA) that we revoke a number of regulations relating to regenerative conditions, for example, disallowing regeneration if brake pressure is not below a set value.

3. Development of KERS

3.1. The Story of On-board Package Development

3.1.1. Development of RA1082 (functionality check vehicle)

The RA1082 was built to demonstrate the advantages of KERS in track tests and find any issues with the conformity of functional components to Formula One conditions. Since the PCU and battery are heavy components, using the RA106 (the 2006 race vehicle) as the base, we altered the area behind the driver's seat inside the monocoque (a CFRP body forming a cockpit) and placed these components there so that we would have little impact on the vehicle's center of gravity. Although placing high voltage components like the PCU and battery in this area has advantages in terms of the vehicle's center of gravity and electrical safety, at the same time it lessens the capacity of the gas bag (fuel tank) located in this area; the gas bag could now hold 83 liters, approximately 40% less than the earlier 140 liters. This was considered a racing strategy issue. As for the motor, originally it should have been directly installed with the engine close to the center of gravity, but because of the engine homologation (development freeze) in effect since 2006, no engine alterations were allowed and connections could not be made to the drive shaft, so the motor was placed inside the transmission case. Giving priority to minimizing the bulge of the case to avoid interfering with the aerodynamics to the rear, the motor gear was connected to the five speed gears of the lay shaft (the driven side shaft). The motor diameter of 100 mm was decided upon based on the installation fastening of the transmission and engine.

3.1.2. Development of RA1089 (race prototype)

We considered the issues of the RA1082 and began designing the RA1089 with the aim of minimizing the impact of KERS being on-board while maintaining a high level of vehicle dynamic performance. This vehicle also had an important position as the winter test vehicle (i.e., pre-season test vehicle) in anticipation of the coming 2009 season. The unprecedented installation layout, offering both vehicle performance and KERS performance, ran into troubles, and even once into chassis production, there were numerous design changes that put a burden on the production site. Moreover, engine changes to install KERS that were originally unapproved were later allowed after a request from Honda to FIA, so the installation of functional components was reviewed again. About that time, the

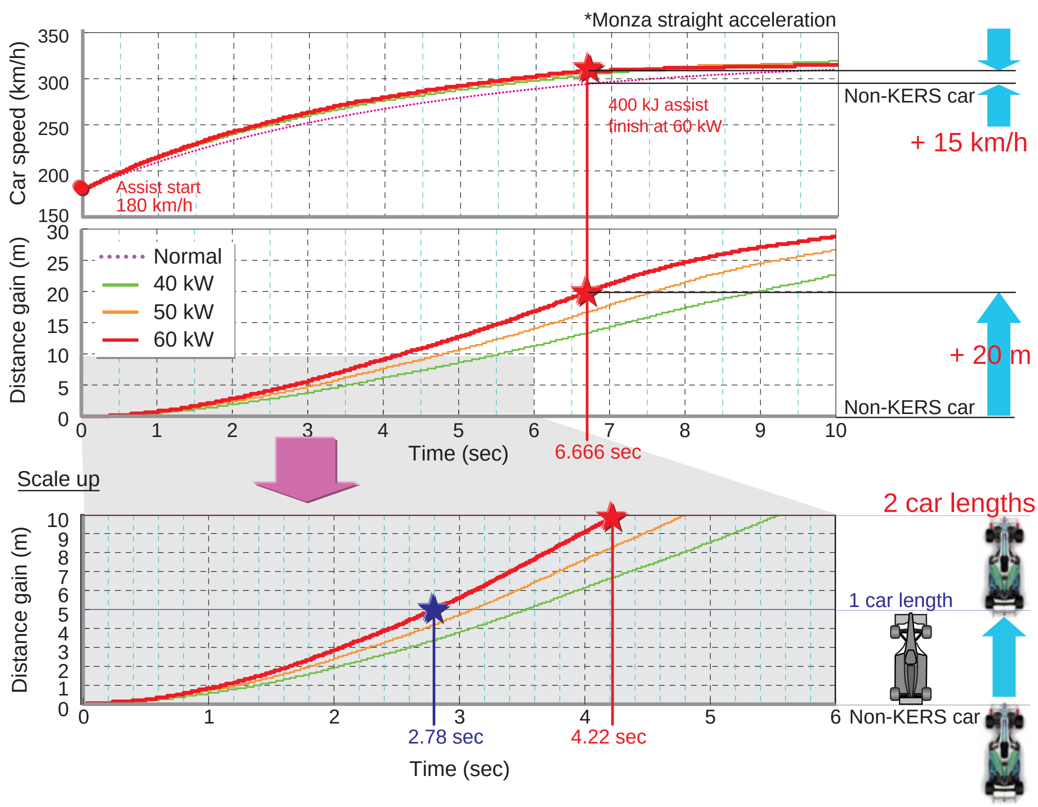


Fig. 2 Assist time / car speed and distance gain

time to decide the chassis layout for RA1089 was already coming soon, but Honda felt that vehicle dynamic performance was the number one priority and so, in a short period of time, worked with the HRF1 engineers to modify the engine and reinvestigate the cooling specifications of functional components and the installation position as determined by all items, including safety in the event of collision. As a result, from the many ideas proposed, it was decided to install the motor on the engine front side, the PCU in the left side pot, and the battery in the monocoque front keel. Table 2 shows a comparative investigation based on motor installation position. This decision not only made it newly necessary to have a motor gear train that connected the engine and motor drive shaft, but there was also an urgent need to ensure toughness against collision for the PCU and battery located outside the monocoque and provide for electrical safety with unprecedented techniques. It was decided to give these the highest priority and reinvestigate the specifications of functional components from the beginning. This put much pressure on the period of stand-alone testing for the PCU and battery, and meant that system launch would have to be taken place in a short period of time.

The next issue was the relative position between the gas bag and motor. If the engine's motor drive is transmitted directly to the crank shaft, it is necessary to put a recess around the gas bag, which is located in front of the crank shaft, of a volume equivalent to the motor. The motor was offset to the left side where it would not impact aerodynamics and the gear train was placed between the back end of the monocoque (the bulkhead) and the engine so the loss of gas bag volume was minimized as much as possible.

Because the functional components underwent completely new development, the challenging work, performed both in Japan and in the UK, dragged on for a long time, so the completion of the RA1089 was delayed. As such, the system check was not in time for the original target of the season's first winter test in November, and the target was changed to the second winter test.

3.1.3. Development of the RA109K (racing specs vehicle)

The RA109K was designed as the racing vehicle. KERS components were located in about the same position as in the RA1089, but in the RA109K, the periphery of the engine cowl, one of the aerodynamic components, was made smaller than in the RA1089, and it was necessary to review from the beginning the forms of the PCU and battery located inside the cowl. Aerodynamic performance is affected by wind tunnel testing time, and therefore aerodynamic components were first produced with a target of being ready for the opening race in March with subsequent updates following in turn. However, the specifications of KERS components cannot easily be changed because we take so long to produce and check for reliability. To ensure development of specifications meeting both these needs,

Table 2 Comparison of motor position

Motor position	Mass	Front-weight distribution	C.O.G
Engine front - LHS	8.69 kg	-0.60%	+1.0 mm
Gearbox	10.30 kg	-1.13%	+1.4 mm

the Japanese and UK bases proceeded with development 24 hours a day until the end of November. In particular, the battery module occupies the greatest volume and weight of all functional components and affects the vehicle's weight distribution and aerodynamics package. The decision on the placement of the battery disrupted the original timeframe for deciding on specifications, but ultimately it was decided to use a dispersed placement, with the battery module located in the keel and also in the nose, a position which until then had not been approved. However, the FIA collision regulations are very strict as far as the nose is concerned, so HRF1 conducted simulations and bench collision tests with the collision regulations to prove the layout's safety and finally earned the FIA's authorization (Fig. 3).

3.2. Overview of KERS

This section discusses the RA109K vehicle intended for races.

Figure 4 shows an overview of the Formula One hybrid system. The motor drive shaft is connected to the engine's cam gear train through the five-gear train for the motor. The motor and PCU were on an anti-vibration mount on the left side of the monocoque, with the motor cooled by engine oil and the PCU by special cooling water. The battery was fixed to the front of the monocoque, and the temperature controlled by the draft air from the front. Besides these modifications, the PCU was connected to the FIA standard ECU (S-ECU) by

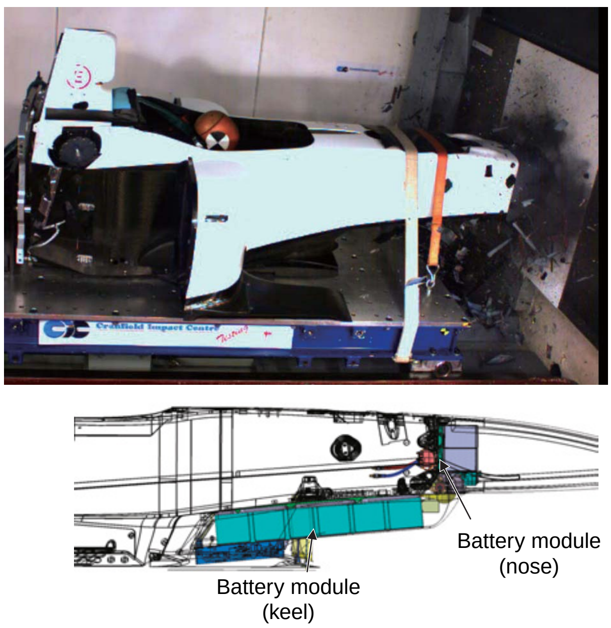


Fig. 3 Front collision test for FIA regulations and battery layout for RA109K

CAN communication for mutual commands and monitoring. Assist and regeneration were controlled in linkage with the driver's operation of the vehicle.

In Formula One vehicles, the vibration environment is more severe than in mass-produced vehicles, so the PCU and battery were built so that even at a vibration of 20 G, there would be no issues in terms of functionality. The motor is required to be able to withstand even greater vibration, because it is exposed to engine vibration, but since this surpasses the capacity of the vibration generator, no stand-alone evaluation was performed; instead, reliability was judged by checking on an engine bench and in track tests. Moreover, in light of collision safety, a structure was chosen that met the FIA's side impact requirements.

3.3. Motor Gear Train

A five-gear train was used as a means of connecting the crank shaft with the motor, which had been moved to the left side of the monocoque. The gears engaged with the engine's cam gear train to connect to the crank shaft (Fig. 5). These KERS-specific parts were made lighter by the use of magnesium covers, titanium bolts and ceramic ball bearings, the use of which is prohibited in the engine itself under the regulations.

There was already only a few mm of clearance between the engine and monocoque, and to put the gear train here required creating some space by putting a recess in the bulkhead. Such a recess diminishes the rigidity of the monocoque and the capacity of the gas bag, so the layout characteristics were enhanced by integrating the gear train housing with the engine front cover. The gear train was in a parallel configuration of five gears with a height of less than 30 mm, but this was the our first experience with a gear train of this form and a technique transmitting torque in both directions, so during development there were frequent issues, such as broken shafts because of resonance in the gears. After subsequent changes of specifications in fine areas and repeated durability testing, we were able to ensure durability in time for track testing.

3.4. Motor

For a motor to be adopted on a Formula One vehicle, it should of course be compact and lightweight and offer high output, and in addition high efficiency is a crucial factor for ensuring enough energy for overtaking; it is no exaggeration to say that this factor determines victory or defeat. A brushless DC motor was therefore used to achieve both of these factors at a high level. From the point of view of installing the motor in the vehicle, as stated before, the diameter was designed to be within 100 mm and the full length within 200 mm, but calculated from required output, the power density is at least 8 kW/kg, which is a far more severe requirement

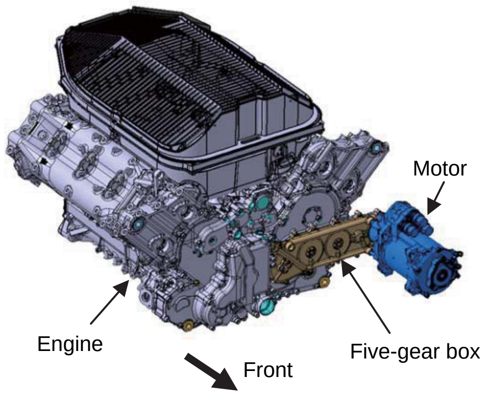


Fig. 5 Five-gear box for motor

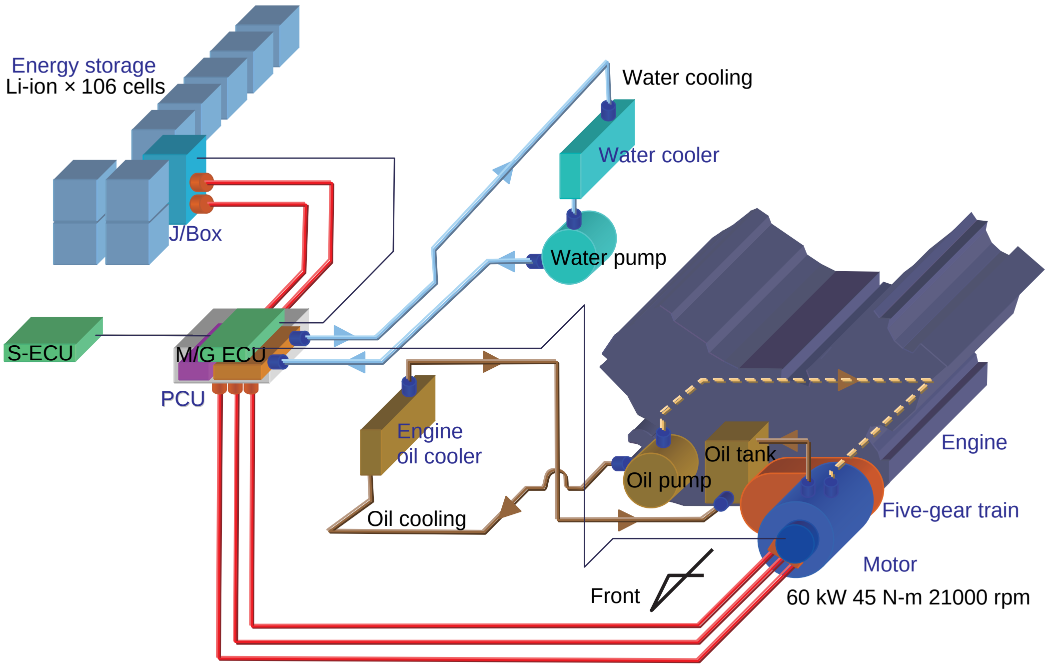


Fig. 4 Hybrid system

than with mass produced motors. Furthermore, we ran KERS simulations with the driving data from past race, and set the requirements that the motor could assist and regenerate up to 60 kW at 13000 rpm and above so that the system could ensure the minimum amount of regeneration on any circuit. To do this, we reviewed the entire motor design, including development of new electromagnetic steel plates and magnetic materials, review of winding techniques and using new cooling techniques and rotor structures, with the result being the achievement of a high power density of 8.7 kW/kg while maintaining high efficiency (Fig. 6).

The rotor used a newly developed high coercive force magnet (iHc = 1.1 MA/m at 160°C) and at the same time, in order to achieve high revolution speed of more than double that of earlier motors, it used filament winding with organic high strength fiber to prevent magnet scattering, thus protecting the magnet circumference. We additionally enhanced torque by 8% by setting a magnetic field angle of θ in, θ out to concentrate the magnetic field orientation of the magnets to the polar center, and divided and stuck the magnets along the length of the shaft to mitigate temperature increases resulting from eddy current loss. For the electromagnetic steel plate making up the stator, on a base of iron and cobalt (49 Fe-49 Co-2 V), we succeeded in reducing eddy current loss by making a 100 µm thin panel, in reducing hysteresis loss with a past-rolling heating treatment, and in enhancing the volume fraction with an oxidized insulation membrane. As a result, saturation magnetic flux density was enhanced by 30% and torque by 15% while iron loss was reduced by 60% as compared to a conventional 200 µm silicon steel panel (Fe-Si). Lap winding was used for the stator winding for high torque and low loss; connecting parts (turnaround parts) at both ends of the stator were press-molded, using injury-resistant copper wire, achieving an unprecedented low connecting (turnaround) height (Fig. 8). Furthermore, because smaller motors made it impossible to keep the coil within the tolerable temperature during driving of the motor in conventional water-cooled jackets with stator housing, a stator structure was used such that the coil ends were directly cooled by engine oil (Fig. 9), so no special radiator was needed. Additionally, the agitation of cooling oil with the rotor increases friction, so a cylindrical cover was used to prevent cooling oil from sticking to the rotor, and the oil chamber of the stator side was completely sealed. As a result, the motor's stand-alone efficiency averaged 95% at an average motor speed of 20000 rpm during assist and 93% at an average of 16500 rpm during regeneration, thereby achieving both high output and high efficiency (Fig. 10).

Fig. 6　Formula One KERS motor

Fig. 8　Core assembly

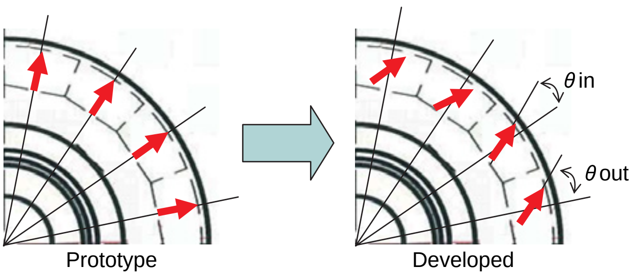


Fig. 7　Direction of magnetization

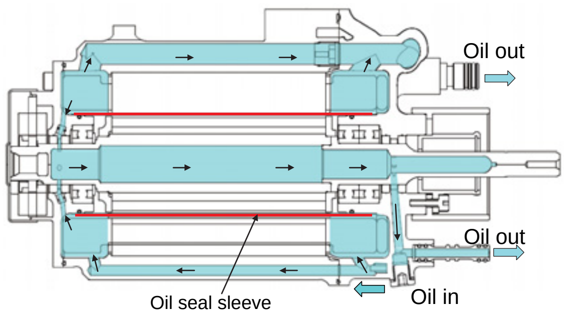


Fig. 9　Section of motor with cooling oil flow

3.5. PCU

The PCU consists of an inverter unit (PDU) to drive the motor and a voltage control unit (VCU) that allows the voltage to be raised or lowered freely. The PCU is used to supply the optimal amount of voltage and current from the battery to the motor and to recharge the battery, and it makes a great contribution to increasing motor efficiency while making it more compact. An intelligent power module (IPM), installed in the PDU, used a special design to enhance compactness and reduce electrical loss, while an SiC diode was used on-board for the first time to reduce flywheel diode noise.

Development of the VCU started out with a boost chopper form, but the PCU also faced severe on-board installation requirements and had to be made smaller and lighter, so system operation frequency was increased and the form was changed to switched capacitor, which offers the potential for a smaller, lighter reactor (voltage step-up coil) (Fig. 11). An effort was made to make the reactor smaller and lighter, not only by increasing the system operation frequency as previously stated, but by forming a 3D core by using dust core materials. However, there is no history of using a switched capacitor system on-board, and the technology was still at the level of proving the principles behind it, so it was difficult to establish the technology, and we were pressed to take measures until just before moving to the circuit for winter testing. The result of their effort was that the PCU was 3.8 kg lighter than that of the RA1082.

The PCU of the RA1082 was located inside the monocoque, but starting with the RA1089 it was hurriedly put outside the monocoque, so that it faced new collision requirements. To meet both the need for lighter weight and collision requirements, we considered changing the aluminum case used up to that point to a CFRP case. In addition, the form of the PCU case was reviewed every time an aerodynamic cowl component was changed because the inside of the cowl, which prioritized aerodynamic performance, had very little installation space.

Under the initial specifications for the RA109K PCU, the unit was cooled by a special cooling water circuit, but to ensure high heat tolerance and low loss, we developed a power module using an Si-C MOSFET (metal oxide semiconductor field effect transistor), and a new heat spreader (silver and diamond compound), thereby creating a smaller, lighter PCU that shared the engine's cooling water; the plan was to release this at the British Grand Prix, midway through the season.

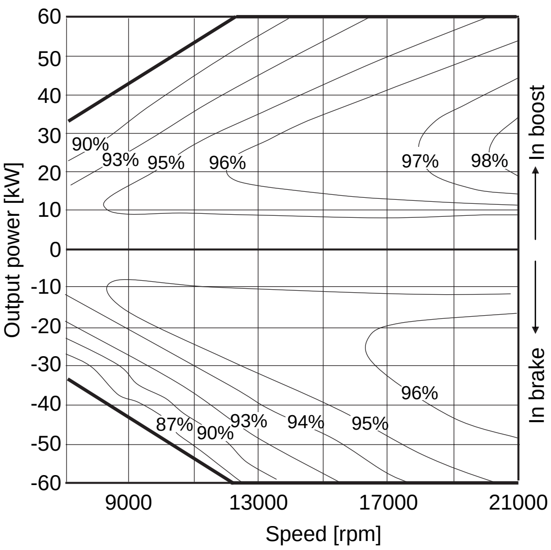


Fig. 10 Motor efficiency

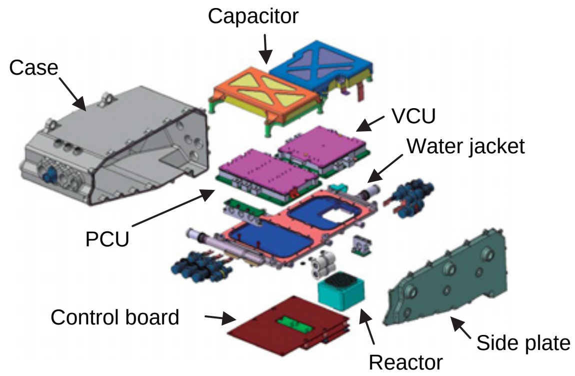


Fig. 12 View of PCU for race specification

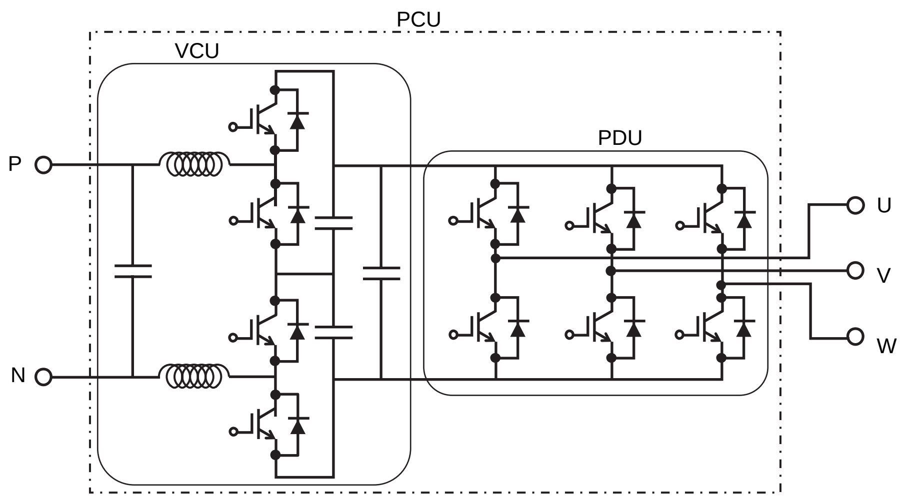


Fig. 11 Race specification PCU block diagram

3.6. Energy Storage

In order to meet the targets for the Formula One KERS, targets for energy storage (ES) were set as below, taking system efficiency into account.

(1) The system should have at least 70 kW at the ES output end and at least 500 kJ of actual charge/discharge energy.

(2) To ensure collision safety, boxes should have at least as much strength as required in the FIA side impact test, with the internal construction having enough strength to withstand at least 100 G-force.

The battery accounts for a high percentage of the weight among KERS functional components, and to get an output of 60 kW, a conventional lithium ion battery weighs at least 30 kg, which reduces the competitiveness of any race vehicle in which it is installed. For that reason, a battery emphasizing output was newly developed based on a lithium ion battery undergoing R&D at that time for ordinary market vehicles. The enhancement of power density continued until just before the system for providing vehicles for the 2009 race season was established. Ultimately, the power density advanced from approximately 5000 W/kg under the RA1082 specifications to approximately 6000 W/kg for the RA109K. This is about five times the power density of a typical Ni-MH battery and about twice that of a typical lithium ion battery (Fig. 13).

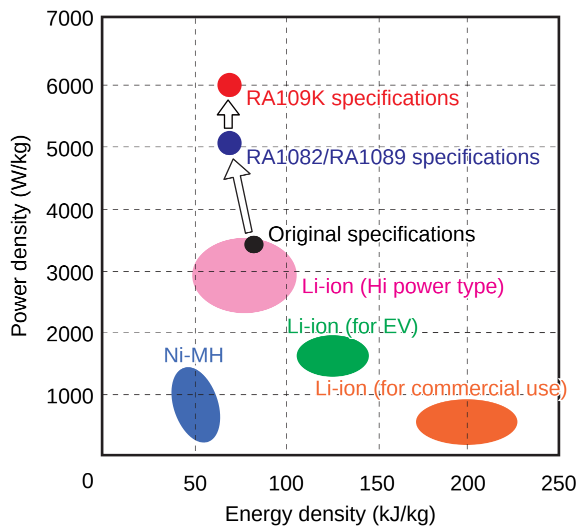


Fig. 13 Battery specifications

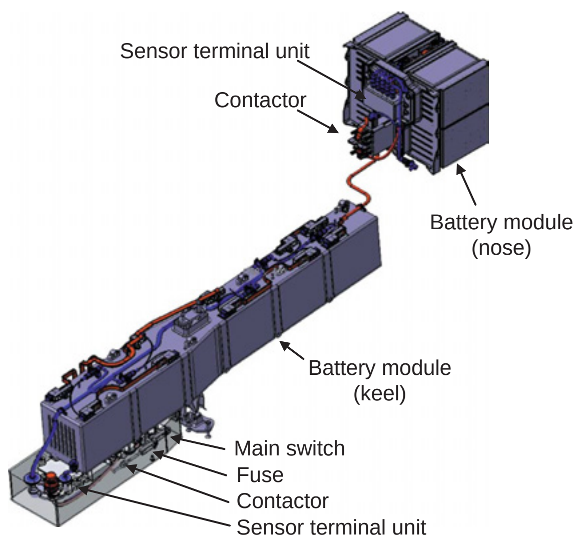


Fig. 14 Battery pack with control unit

On the other hand, the battery of the RA109K was split for installation into two areas, the nose and the keel, to meet the collision requirements. To minimize the impact on vehicle weight, the cooling system depended on draft air from the front of the vehicle; for waterproofing, cell connections and high voltage terminals were molded when building the single module. Furthermore, sensor terminal units, which constantly monitor cell temperature and voltage, were placed in each battery box (Fig. 14).

3.7. High Voltage Safety

Honda's basic stance on high voltage safety is that high voltage components should be placed in an area that is unlikely to be crushed even in the event of collision. In races, however, for reasons of strategy and vehicle packaging, KERS high voltage components were placed outside the monocoque and could therefore potentially be crushed. To ensure high voltage safety under these conditions, we decided that it would be necessary to actively announce our proposal for safety measures as based on mass production experience when implementing KERS, and Honda put together its own safety stance prior to the FIA's move to implement unified safety standards. The high voltage power source in KERS consisted of the following three units.

- High voltage battery
- PCU capacitor (when recharging)
- Motor (counter electromotive force is generated when the motor is turned by external force)

To ensure high voltage safety, it is important that KERS unit and cables be securely insulated. Furthermore, if it is possible that the insulation can be destroyed by accident or contact with another vehicle, it is necessary that the supply of high voltage from the above three units definitely be cut off. Consideration also needed to be given to removal of the insulating structure (the covers, case, and the like) when performing maintenance. It is also important to provide a monitoring function (ground fault detection). Based on the above perspectives, safety was ensured with the specific structure below.

3.7.1. Safety during collision

(a) Destruction of the insulating structure (case and covers) by loads anticipated during collision was prevented. Specifically, enough strength was ensured that the insulating structure would not be destroyed under conditions equivalent to those of the FIA's side impact test.

(b) In the following cases, the electric charge in the PCU capacitor was discharged at the same time the main contactor was cut off.

- When the FIA driving data inspection record unit that

is connected to the S-ECU has detected acceleration beyond a set value
- When the acceleration sensor on the PCU control board has detected acceleration beyond a set value

Specifically, the electric charge was shifted between the VCU's two capacitors by VCU switching, and electric energy was changed to heat and released by switching loss and conduction loss.

(c) A circuit that discharges electric charge from within the PCU capacitor if the control power source supply is cut off was located on the control board.

(d) A structure was used such that the high voltage connector keep plate would be destroyed if more load than anticipated were applied. The load required to destroy the plate was set to be smaller than the load to break cables, so that in the event of collision, connectors would come off before high voltage wiring breaks (Fig. 15).

3.7.2. Safety during maintenance

(a) The electric charge in the PCU capacitor was discharged at the same time the main contactor was cut off, when the ignition was off.

(b) A structure was used such that an interlock mechanism was used for the DC cable connector and high voltage would not be applied to terminals when high voltage connectors were removed. To remove or put on the high voltage connector cover, one had to remove the control harness, and if the control power source were cut off, the PCU would discharge and not apply high voltage to connectors. A similar structure was also used on the battery side to ensure safety.

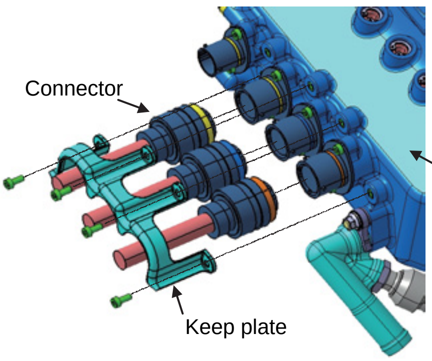


Fig. 15 Structure of high voltage connectors

3.7.3. Ground fault detection system

A detection circuit was mounted on the PCU control board, and during KERS operation (i.e., when the main connector is connected), the high voltage area ground fault detection system was constantly put into operation. Safety was ensured by making a warning lamp turn on and simultaneously cutting off the main connector when a ground fault is detected.

3.8. Control

KERS control system consisted of an S-ECU control and PCU control (Fig. 16).

The S-ECU control calculated electric power commands based on driver operations and monitored motor output and per-lap assist energy. Assist occurred when the driver pushed an assist button with the accelerator pedal fully depressed, while energy regeneration only occurred when braking. Motor output was measured using values from torque sensors, and other values, and if it was determined that a violation had occurred, an output restriction penalty lasting a few seconds was imposed. Assist energy was calculated from the total motor output, and assist was stopped when 400 kJ was reached.

To use KERS to its full capacity, one has to use the 400 kJ efficiently and recover enough energy to make that possible. Trial calculations indicated that to get 400 kJ of assist, one needs about 500 kJ of regenerative energy, taking into account such factors as loss depending on system efficiency and the energy consumed by zero torque control. Because carbon disk brakes have good brake force and can slow down vehicles quickly, it is conceivable that if regenerative torque is added, brake force will be unstable and stability will decline, and we predicted that depending on the circuit, road surface conditions and other factors, it may not be possible to perform regeneration sufficiently and thus there would not be enough energy. We therefore

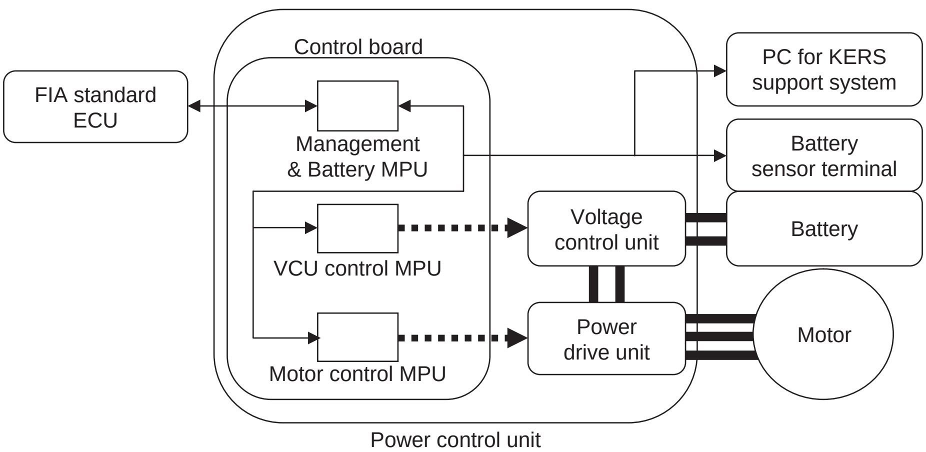


Fig. 16 Control system configuration

optimized each control component, including cooperative control, and also optimized control of each functional component by incorporating the various simulation results into specifications. Through track tests, we also endeavored to optimize the front-to-back brake balance and distribution of regenerative braking and engine braking. These tasks all require a high level of balance, and track test settings were predicted to be difficult because we are subject to S-ECU function limitations and annual mileage limitations, but drivers were not demanding any enhancements and potential issues were considered unlikely for initial specifications.

It was decided that the operation of starting assist, which is entrusted to the driver, would take effect at the lowest vehicle speed, at which excessive driving force would not result in wheel spin. This was to simultaneously prevent both an unnecessary increase in the driving force in low gear due to motor torque and a decline in assist efficiency resulting from an increase in driving resistance. Acceleration by assist is also affected by gear ratios and aerodynamics settings, so the amount of time and energy needed to overtake on each circuit was calculated and the effectiveness clarified, and results were used effectively in determining ES capacity and designing how each functional component would be cooled.

In the PCU control, each functional component was controlled based on electric power commands from the S-ECU control. This consisted of PCU management control, motor control, VCU control and battery control, and the necessary functions were created for racing use based on existing specifications.

The system operations such as system stop and output stop or power save were determined using PCU management control, based on mediation between electric power commands and system status.

Motor control and VCU control controlled motor output. Because of the motor's connection to the gearbox in the RA1082, it was necessary to have some control so that torque would be lost instantly (torque loss control) when downshifting. When downshifting, on the other hand, energy regeneration was performed while decelerating, so torque loss control, during which energy could not be regenerated, should be applied in as short time as possible. If responsiveness were to be within 50 msec as stipulated in the regulations, the time it would take to recover from torque loss control would be wasted, since energy could not be regenerated then, so we targeted responsiveness of within 15 msec to reduce wasted time. It was decided that electric power commands would change step-wise, at each change of gear, from -60 to 0 kW or from 0 to -60 kW, and we had to ensure controllability during great fluctuations of revolution speed and load. For motor control, current feedback control was performed using vector operations, but the behavior of field component current in response to step-wise electric power commands could not be fully controlled and excessive current sometimes occurred. For VCU control, output voltage feedback control was performed, but this arrangement could not keep up with sharp load fluctuations and excessive voltage frequently occurred. The countermeasures against these issues continued until just before track tests, and we were able to achieve both stability and responsiveness to the target of being within 15 msec by enhancing their techniques for calculating target current values with motor control and by applying voltage with feed-forward items in both control parts.

In addition, we unstintingly added the technological elements deemed necessary to the pursuit of speed, such as performing zero torque control during ordinary driving (without assist) with motor control to prevent interference with engine acceleration. We furthermore developed one-pulse control, which set the former pulse width modulation (PWM) duty to 100% and reduced the number of times switching occurred in order to minimize PDU loss, and also developed VCU variable-voltage control to maximize motor efficiency, with the aim of releasing these developments during the 2009 winter tests. These systems were also subjected to cooperative control and systems were optimized simultaneously.

For battery control, we made it possible to use lithium ion batteries safely and efficiently by monitoring battery voltage and temperature as found at the sensor terminal and accurately determining charge status as based on calculation of the amount of electric power charged and discharged.

4. Bench Tests and Track Tests

4.1. Bench Tests

Two Formula One engine test benches were used, to check the system and its durability. A battery simulator (BTS) and inverter stand (Fig. 17) were implemented along with these benches to make them KERS-compatible. A completely new BTS was implemented to deal with a level of responsiveness unprecedented in mass produced vehicles, making it possible to test the overall system with all parts assembled (the engine, motor, PCU, battery, and other parts) in coordination with development of the RA1089 without experiencing troubles under transient loads equivalent to actual driving.

In this way, we substituted the bench for all testing from confirming operation of each functional component of KERS system to confirming the functionality of the

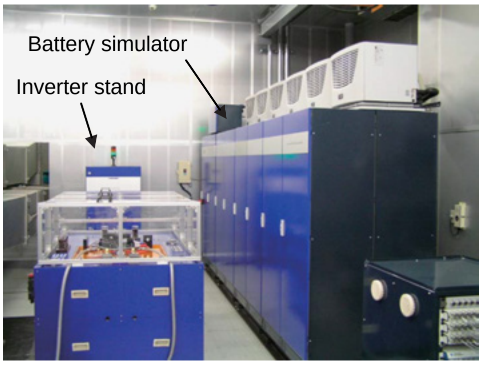


Fig. 17 Battery simulator and inverter stand

overall system on an actual vehicle, including functional assurance testing, and sought to bring KERS as a whole to early fruition without the track tests that are so severely restricted under the regulations.

Figure 18 shows the basic form of the test bench. KERS was mounted with the engine as part of the jigs. Using bench testing equipment, miscellaneous evaluation tests were performed as shown in the events of Table 3, under steady state or transient load conditions. For the transient load tests on the bench, the system underwent mode operation, reproducing actual driving conditions based on circuit data from actual driving experience, and transient performance evaluation, particularly energy management, measurement of the temperature of each part, and the like, was performed, making it possible to acquire useful data and obtain feedback in order to speed up development. Figure 19 gives a typical example of mode operation.

The data in the figure was acquired with the following combination. This experience demonstrated that it is possible to conduct function and durability bench tests before actual circuit driving.

- Driver: Jenson Button
- Circuit: Monza
- Car: RA1082 + KERS

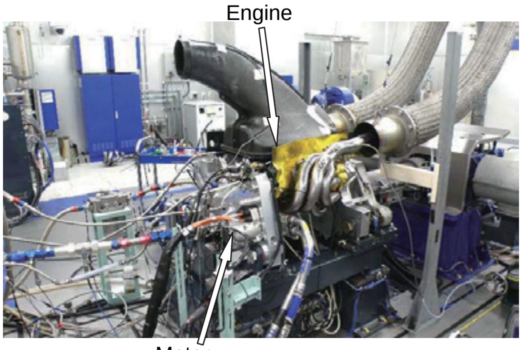


Fig. 18　Combination examination of engine and motor

Table 3　Testing items on engine dyno bench

Function test	-System operation / setting -System output -System efficiency -Fail safe action -Temperature measurement -Vibration measurement -Gear behavior -Oil pressure measurement -Tool operation check
Durability test	-Engine and KERS parts durability test -Energy management

With the RV (real vehicle) bench [(1)], furthermore, it was possible to mount an actual Formula One monocoque and cooling system on the bench and perform a variety of tests in an actual vehicle environment in addition to the above power train test bench environment (Fig. 20). The RA1082 was actually placed on the RV bench so that countermeasures for electrical noise that was unique to KERS were completed before driving on a circuit. Admittedly, because of the

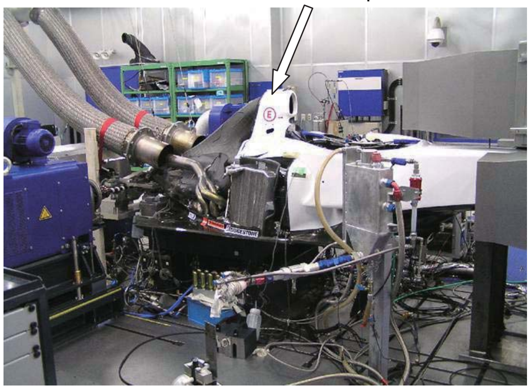


Fig. 20　Bench examination using RV bench with real Formula One KERS car

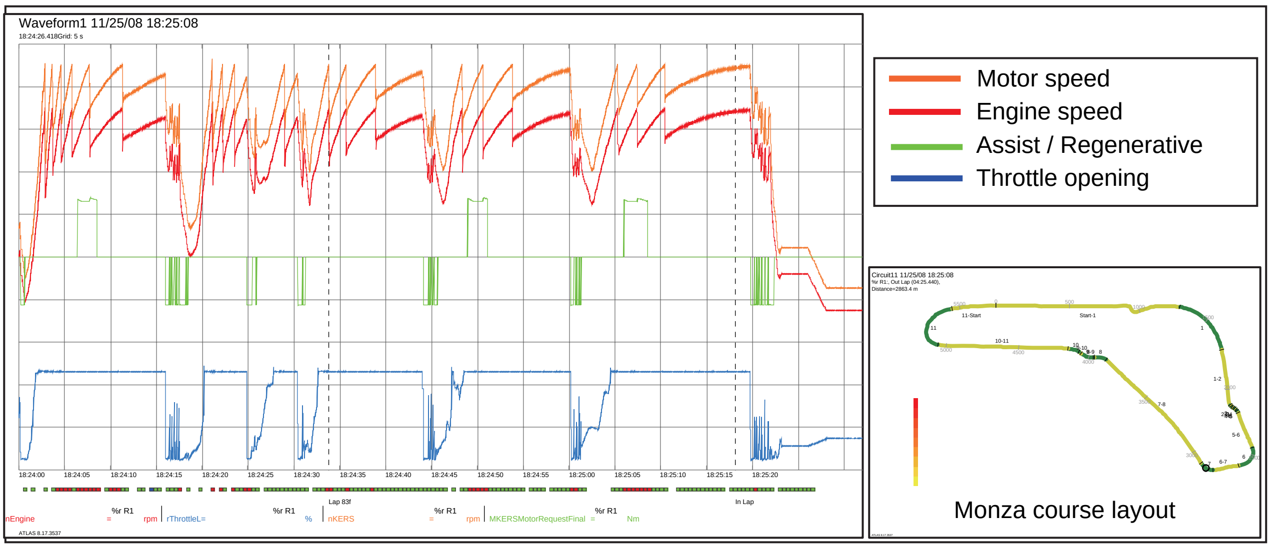


Fig. 19　Circuit mode test on dyno

Table 4 Durability test results of dyno

Event	Purpose	Mileage
KE-01	Check environment and first issue parts	238.4 km
KE-01.5	Check track-1 specification parts	465.4 km
KE-02	Track test simulation (for Jerez circuit)	611.0 km
KE-03	Check track-2 specification parts	748.8 km
KE-04	Check race specification parts	1351.9 km
KE-05	Check engine gear durability with extreme circuit mode (test stopped due to schedule)	566.1 km

production schedule, the RV bench was not used with subsequent vehicles, but power train durability was tested on the bench prior to circuit driving and mileage equivalent to more than two race events (1350 km) was assured with all functional components (Table 4).

4.2. Track Tests

In late April 2008, HRF1 conducted the shake down of the RA1082, the first machine with KERS, and subsequently conducted actual driving test four times with the RA1082 and twice with the RA1089.

RA1082, the first actual vehicle, underwent modifications and the vehicle was finally complete four days prior to shake down, which cut deeply into the originally planned two weeks of system checks, and with vehicle settings, additional modifications, and the like, there was in effect a preparation period of only about two days. The track test members had to deal with the system operations check and initial troubles in a short period of time and were not able to get to complete operation by the prescribed date. For that reason, in the initial shake down we decided to maintain the electric current status, and to limit themselves to checks of system safety and the function of functional components. At HRF1, we were not able to confirm system operation by chassis dyno as with the RV bench, so all we could do was to check system operation by firing-up the engine in a factory. However, to fire-up the engine required a large number of engineers and mechanics and a launch sequence starting several hours in advance. For the sake of engine durability, moreover, it is not possible to let it run for long periods with no load, so we could only get the desired data in a very short period of time, and it was difficult to do system check of KERS. Ordinarily fire-up only takes place once or twice before shake down, but fire-up was conducted dozens of times with the RA1082. The first shake down was not done under the maximum load allowed by regulations, but the run was memorable for being the first KERS actual driving test among all 10 Formula One teams. At the factory, we subsequently responded to nonconformities found during shake down, and a week later conducted output and regeneration tests on the Silverstone Circuit, confirming that KERS functioned effectively under Formula One conditions. The team subsequently made more enhancements, conducted a private test in July and took part in a joint test at the Jerez circuit in Spain in September, thus beginning the first regular run on a circuit (Fig. 21). The benefits of KERS were verified at the maximum load under regulations at the Jerez circuit; the following benefits were confirmed.

(1) As Fig. 22 indicates, lap times were reduced by approximately 0.4 seconds when assist with energy of about 400 kJ per lap was applied.

(2) As shown in Fig. 23, car speed increased by 7 km/h with distance gain of 7.8 m (1.6 car lengths) with continuous assist of 324 kJ on one straightaway.

Because the amount of tire skidding and aerodynamic specifications, including speed during assist and road surface conditions, differed from initial simulation results, there was some discrepancy in values, but the effectiveness of KERS was sufficiently demonstrated.

A driver who experienced the full power assist of KERS commented, “I was impressed by how amazingly

Fig. 21 KERS car and engineers

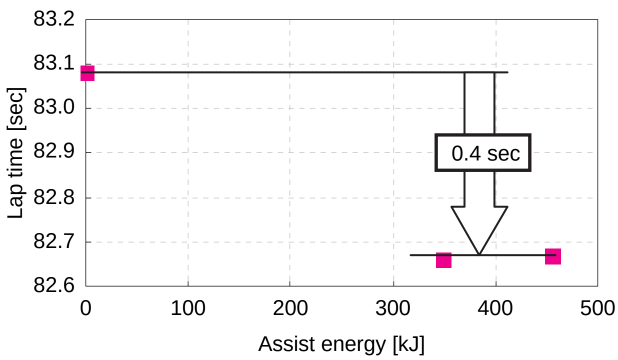


Fig. 22 Lap time against the assist energy

fast I approached the hairpin when the assist kicked in. It makes acceleration from the engine alone feel as if carrying a heavy weight."

Then the RA1089 was completed in November 2008 ahead of winter testing. However, the system of the RA1089, mounted with a new VCU as described earlier, is very different from that of the RA1082, and so noise frequently resulted in system failures, and together with bench analysis, day after day was spent in noise analysis on actual vehicles and discussions on countermeasures. For the RA1089, the HRF1 engineers, mechanics and other track test members worked together to conduct more than 100 fire-ups, more than we did with the RA1082, with the result that we overcame all the troubles. This was the result of all the members, from the UK and Japan, coming together to solve some very difficult issues.

Then on November 28th, the RA1089 underwent shake down on the straight course of Santa Pod in the UK (Fig. 24), confirming that all systems were operating normally, and since the judgment was made that the system could be used on a circuit, the RA1089 and its equipment were loaded onto a trailer on the evening of December 4th as the test vehicle for joint testing on

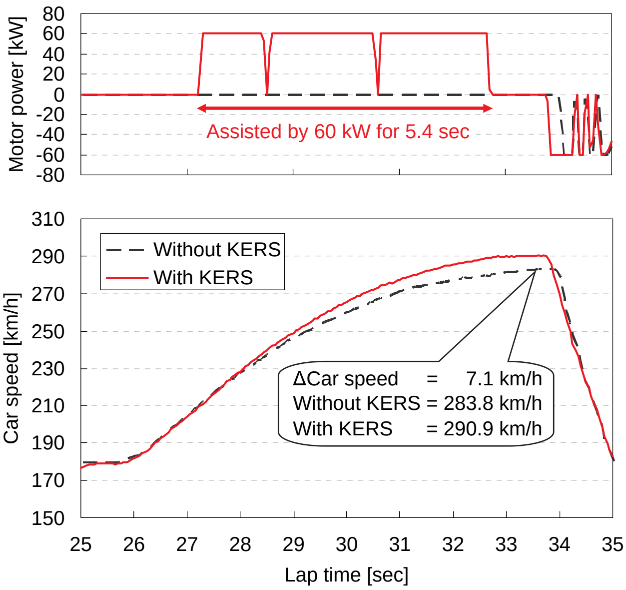


Fig. 23 Car speed comparison

Fig. 24 Launch of the RA1089 with KERS system

Table 5 Track test results of KERS car

Date	Circuit	Driver (chassis)	Mileage	Notes
29-Apr	Santa Pod	A. Wurz (RA1082)	2.4 km	Shake down
7-May	Silverstone (short course)	J. Rossiter (RA1082)	25.0 km	Shake down 25 kW assist 35 kW recharge
29-Jul	Silverstone (Stow School)	M. Conway (RA1082)	48.6 km	Shake down 60 kW assist 60 kW recharge
16-Sep	Jerez*	M. Conway (RA1082)	88.6 km	60 kW assist 60 kW recharge
19-Sep	Jerez*	A. Wurz (RA1082)	225.8 km	60 kW assist 60 kW recharge
13-Nov	Kemble	A. Davidson (RA1089)	10.5 km	Shake down
28-Nov	Santa Pod	A. Davidson (RA1089)	33.5 km	Shake down 25 kW assist 25 kW recharge

*: Full race track

December 9th at Jerez. On December 5th, however, it was announced that Honda was pulling out of Formula One racing, and all activities ceased, which meant that the shake down of November 28th was the last track test of Honda's third-era Formula One activities. The record of KERS circuit track tests is given in Table 5.

5. Conclusion

The effort to develop an electrical hybrid system that intended to introduce KERS in 2009 produced the following results.

(1) A compact lightweight hybrid system was developed and a car was produced with performance to realize maximum output of 60 kW and 400 kJ of assist on each lap of a circuit.

(2) Honda became the first in the world, beating out other companies, to conduct actual driving tests of KERS on a circuit, and demonstrated faster lap times with KERS (about 0.4 sec faster with 400 kJ of assist) and the effect of an overtaking boost (about 7 km/h with assist of 324 kJ).

(3) The team demonstrated the safety of KERS in all processes in the development of functional components and the vehicle, as well as in circuit driving.

Afterword

The development effort was confusing at first, because several things were happening simultaneously: R & D on completely new KERS functional components, all staff members concerned with KERS – the technical development staff, race engineers, the mechanics, other site managers, vehicle production staff, and vehicle electrical equipment staff in the UK and Japan – receiving training and mastering high voltage systems, cooperation with the FIA on safety, and working to revise regulations. But the fact that the development took place in such an unusually short period of time (nine months from the start of development until first driving, and 15 months until shake down of the racing specs vehicle), is a tribute to the joint development system with the HRF1 members, overcoming language barriers and national borders and showing mutual respect, and to the joining of minds of everyone concerned, including cooperating manufacturers, those involved in distribution, business travel and translation, and local staff. This is something all members are proud of.

Reference

(1) Nakamura, S., Motohashi, Y., Hayakawa, S.: Development of Wind Simulator Equipment for Analysis of Intake Phenomena in Formula One Engines, Honda R&D Technical Review, 2009, F1 Special (The Third Era Activities), P. 95-100

■ Author ■

Masataka YOSHIDA

Masato KITA

Hirofumi ATARASHI