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# Development of the ultra-low-fuel-consumption hybrid car – INSIGHT

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**Abstract**

This paper describes the key technologies that achieve high fuel efficiency in a variety of driving conditions. For the global environment preservation, a vehicle has been developed with the objective of reducing fuel consumption and exhaust $CO_2$ to half that of Honda's typical low-fuel-consumption car Civic. These new technologies have been developed around a new hybrid power train layout. They include improvement in engine thermal efficiency, vehicle weight reduction and reduction of aerodynamic drag, resulting in extremely high fuel economy of 35 km/l at 10–15 mode. Also, the exhaust emissions are as low as half of the 2000 Japanese exhaust emission regulation. Consideration was also given to recycling compatibility, crash safety performance, comfortable running and styling to create a highly sophisticated ultra-low-fuel-consumption hybrid car. 

## 1. Introduction

Automobile manufacturers are being challenged with increasingly strict environmental requirements to lower automobile fuel consumption and reduce emission levels.

Honda has already introduced mass-produced vehicles that achieve low emission levels, corresponding to one-half the post-53 exhaust gas emission standard. This has been accomplished through the practical application of technologies such as the variable valve timing and lift electronic control system (VTEC) [1], metal honeycomb catalyst [2] and quick engine warm up system during fast idle [3]. Honda is now working on another major environmental objective of reducing the $CO_2$ level by achieving an unprecedented low level of fuel consumption.

In order to accomplish this, a new concept for the hybrid power train system is created. The concept includes numerous new techniques for improving the efficiency of the engine, reducing the weight of the body and reducing aerodynamic drag. The result is a vehicle with extremely low fuel consumption, approximately 35 km/l in the Japanese 10–15 mode.

A description of the resulting hybrid car is reported here.

## 2. Development goal and concept

The object of this development was to achieve low fuel consumption. The goal was to achieve the best fuel economy in the world, or one-half of the low fuel consumption Honda Civic.

Since emissions performance all too frequently tends to be sacrificed for lower fuel consumption, it was also decided to ensure a low level of exhaust emission comparable to that already achieved with other mass-produced vehicles.

Emphasis was also placed on recycling capability, another important environmental area, while also giving full consideration to collision-safety performance, vehicle dynamic characteristics and styling.

The development concept therefore had the following objectives:

- The lowest fuel consumption of comparable vehicles.
- Low exhaust emission.
- High recycling capability.
- High collision safety.
- Advanced styling.
- Practical and maneuverable handling.
- Two-seater, personal utility space.

## 3. Method for achieving low fuel consumption

To help identify areas for reducing fuel consumption, a detailed analysis was conducted on the energy consumption of a Civic equipped with a 1.5-l engine, which was the base vehicle used to examine various system


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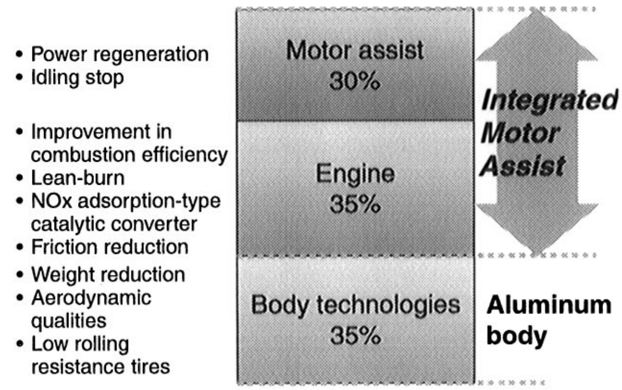


Fig. 1. Rate of contribution to achieve an improvement in fuel economy (10–15 mode).

types. It was found, as shown in Fig. 1, that each of the following actions would need to play roughly equal roles in order to achieve the objectives:

- Improvement of the thermal efficiency of the engine.
- Recovery of braking energy and an auto idle stop system through the use of a hybrid power train.
- Body and chassis improvements to reduce weight, decrease aerodynamic drag and rolling resistance.

## 4. Hybrid power train

### *4.1. System configuration*

As shown in Fig. 2, the hybrid drive system uses an internal combustion engine for the main power source and an electric motor for auxiliary power when acceleration is required. This system has been named Integrated Motor Assist (IMA). It is a parallel hybrid system in which a DC brushless motor is installed between the engine and transmission. The motor is used only as an auxiliary power source. The overall design of the system is simple and minimizes the size and weight of the motor, battery and power control unit (PCU).

During acceleration, the amount of auxiliary power required (referred to as assist) is calculated from the throttle opening, engine status, battery status and other parameters. The amount of current from the battery is controlled by the PCU to drive the motor. Motor assist during acceleration allows the use of a smaller engine without affecting vehicle performance. This reduction in engine displacement is the most important factor for improving the fuel consumption with a hybrid system. During deceleration, regenerative braking (regeneration of the vehicle kinetic energy into electrical power) is applied according to the brake pedal force and vehicle speed. The resulting electrical power is used to charge the nickel hydride battery.

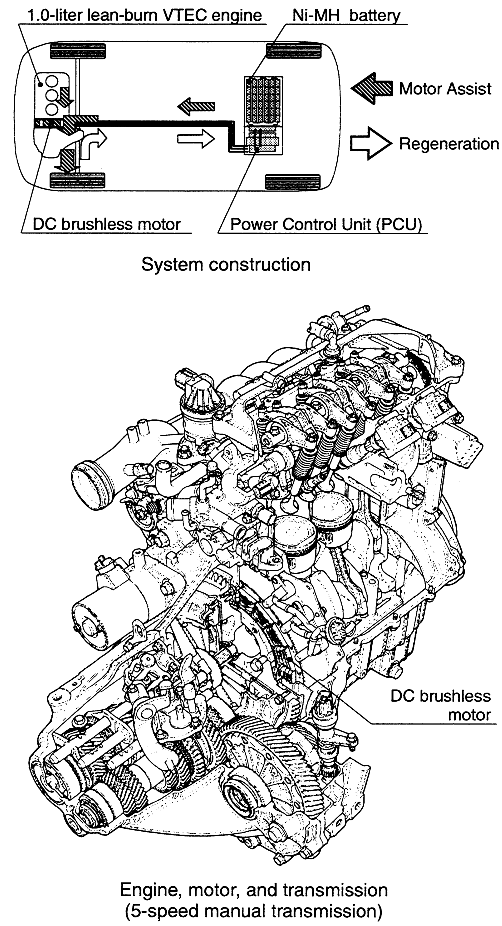


Fig. 2. IMA (integrated motor assist) system.

### *4.2. Motor assist function*

The motor assist function of the IMA system was designed to achieve the following two objectives by limiting its functions to motor assist during acceleration and regenerative braking during deceleration:

- Simple, compact construction.
- System weight equal to no more than 10% of the vehicle weight.

#### *4.2.1. Thin-type DC brushless motor*

The motor providing assist power and energy regeneration is a permanent magnet-type, three-phase synchronous electric motor having a maximum output of 10 kW with high efficiency, compact size and light weight. Emphasis was placed on minimizing the width of the motor to make the drive train as compact as possible.

The rotor is coupled directly to the crankshaft. The lost-wax precision casting process is used to reduce rotor weight by about 20%, while providing high strength and rigidity. The rotor magnet benefits from improvements to the neodymium sintered magnet used in Honda's electric

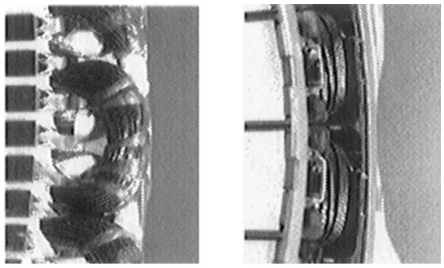


Fig. 3. Comparison of winding.

vehicle, the EV PLUS, to achieve a roughly 8% improvement in performance with improved heat resistance. The result is a high-performance motor that does not require a cooling system. As shown in Fig. 3, the stator is of the split type, enabling a more compact size and more efficient salient pole centralized windings than would be possible with conventional coil windings. In addition, the use of a centralized distributing bus ring, in which the electrical harness is formed in a copper plate, for each stator coil reduces size and simplifies construction. The result is a motor thickness of only 60 mm, 40% less than would be possible with a conventional motor.

*4.2.2. Nickel hydride (Ni-MH) battery*

The battery used for motor assist is characterized by its stable output characteristics, regardless of the degree of charging, and by its outstanding durability. This nickel hydride battery already has a proven track record in the EV PLUS. Changing the shape of the battery from square to cylindrical reduced both the size and weight. The battery pack comprises six 1.2 V cells connected in series to form a single 7.2 V module. Twenty of these modules are arranged in the form of a lattice to create an integrated structure. The resulting 120 1.2 V cells connected in series provides a total of 144 V from the battery pack.

*4.2.3. Power control unit (PCU)*

The PCU is responsible for precision control of motor assist and regeneration, as well as the supply of 12 V power. The built-in cooling minimizes the size and weight of the PCU. The cooling system and PCU are integrated into a single unit equipped with a highly efficient cooling fin and magnesium heat sink, resulting in a particularly low weight.

The inverter for motor assist, which is the most important component of the PCU, was reduced in size by integrating the switching device generating three-phase alternating current into a single module. Each phase was separated in the EV PLUS. The Insight inverter also includes a drive circuit in an IC. These changes resulted in a considerable reduction in weight and improvement in power conversion efficiency. In addition, controlling the phase angle to maintain the most efficient motor operation reduced the amount of heat generated and made it possible to use an air-cooling system to simplify and lighten the PCU.

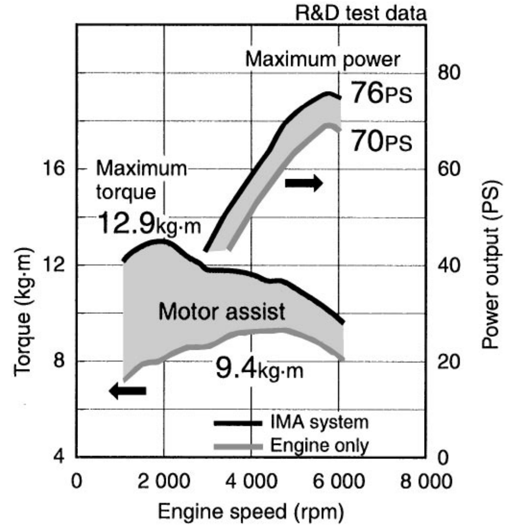


Fig. 4. Output performance of IMA system.

*4.3. Deceleration energy regeneration*

Increasing the amount of energy available from the regenerative braking system made it possible to increase the amount of electrical energy available for assist during acceleration, leading to a reduction in fuel consumption by the engine. Since reducing the running resistance and the resistance from engine braking both increases the amount of regenerated energy, a smaller engine displacement will contribute to increased regeneration energy. In addition, the IMA system optimizes the operation of the engine and transmission to gain the maximum amount of recovered deceleration energy.

*4.4. Optimizing the engine displacement*

As mentioned previously, reducing the engine displacement is the most important factor for improving the fuel consumption with a hybrid system. However, this can also reduce the available power from the engine. The IMA system uses electric motor assist to provide high driving torque at low engine speeds. At high engine speeds, the inherent characteristics of the VTEC engine are taken advantage to ensure sufficient power under all driving conditions. These characteristics are shown graphically in Fig. 4. This integrated system allows the use of an engine with a displacement as small as 1.0 l.

*4.5. Lean-burn engine combustion*

For further improvements in engine thermal efficiency, lean-burn operation is used during light engine loads.

The linear torque characteristics of the electric motor at low engine speeds reduce the load on the engine. It expands the range for lean-burn combustion without impairing driveability. This also contributes to reduced fuel consumption.

### 4.6. Auto idle stop system

Stopping the engine when the vehicle is stationary is another effective means of minimizing fuel consumption. The engine is not started until after the motor has spun the engine up to 600 rpm or higher, so no fuel is consumed during starting which further minimizes the fuel consumption.

Auto idle stop with the Honda Multi Matic S (CVT) is controlled hydraulically by using an actuator and hydraulic circuit that enhances hydraulic response. Restarting is assisted by an electronically controlled starting clutch to provide enhanced starting response.

The auto idle stop system is also incorporated in vehicles equipped with a manual transmission. The system uses a neutral switch and a clutch pedal switch to make a comprehensive evaluation of the vehicle movement and driver operation.

## 5. Engine

Engine development focused on the following three points to minimize fuel consumption:

- Improved combustion.
- Reduced mechanical loss.
- Compact size and light weight.

In addition, the target for the exhaust gas emission level was set as one-half the post-53 exhaust gas emission standards.

### 5.1. Engine overview and main specifications

The engine specifications are shown in Table 1, while the major technologies employed in the engine are shown in Fig. 5. A three-cylinder engine was selected to provide the optimum combustion chamber $S/V$ ratio and to minimize mechanical losses.

A long-stroke configuration with a stroke/bore ratio of 1.13 was selected to achieve the best balance between a compact combustion chamber size and mechanical loss of the pistons. A lean-burn combustion system was applied, using intake swirl from the VTEC-E system, to simultaneously realize low fuel consumption over a wide driving range, low exhaust gas emissions, and adequate power output.

Table 1
Engine specification

| | |
|---|---|
| Engine type | Water-cooled gasoline engine |
| Cylinder layout | In-line 3-cylinder |
| Bore × stroke (mm) | ø72 × 81.5 |
| Displacement ($cm^3$) | 995 |
| Compression ratio | 10.8 |
| Valve train | SOHC VTEC 4 valves per cylinder |
| Cam shaft drive train | Chain drive |
| Maximum power (kW/rpm) | 51/5700 |
| Maximum torque (N m/rpm) | 92/4800 |

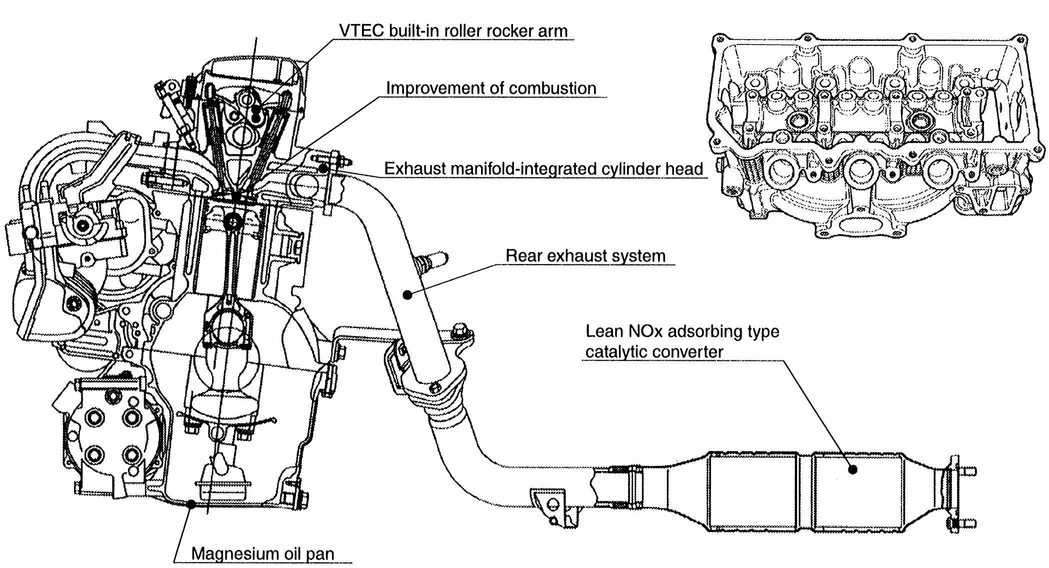


Fig. 5. Main technologies of the engine.

### 5.2. Improvement of combustion

This engine is characterized by significantly improved combustion efficiency through the use of lean-burn combustion technology. A new swirl port that enhances fuel–air mixture turbulence and swirl in the cylinder and a compact combustion chamber with a high compression ratio for high thermal efficiency are employed. The result is a combustion time that is much shorter than that with conventional lean-burn engines, allowing combustion in a leaner range with significantly reduced fuel consumption and lower $NO_x$ emissions.

This combustion chamber is a more advanced form of that used in our conventional VTEC lean-burn combustion engine. In the conventional VTEC-E engine, swirl is generated by closing one of the intake valves. In this new engine, the intake valves and intake ports are arranged in a more vertical direction, resulting in the generation of a powerful eddy in the air–fuel mixture that enter the cylinders.

The configuration of the conventional VTEC engine provides separate rocker shafts for the inlet rocker arms and exhaust rocker arms. The newly developed VTEC mechanism integrates these separate rocker shafts into a single rocker shaft. This results in a much more compact rocker box and allows the valve-included angle to be narrowed from 46° to 30°. The narrower angle allows the port shape and compact combustion chamber to be configured for generating powerful swirl.

### 5.3. Reduction of mechanical losses

In addition to modifying the combustion chamber design, it was also important to reduce the fuel consumption by minimizing mechanical losses.

The following methods were applied to reduce friction:

- Roller coaxial VTEC.
- Piston dimple treatment.
- Offset cylinders.
- Low-tensile piston rings.
- Carbonized connecting rods.

The roller coaxial VTEC construction applies the technology used in the S2000 [2] to a single camshaft VTEC mechanism. A needle bearing is employed for the journals of the rocker arms that are in contact with the camshaft, reducing the normal drive loss of the camshaft by roughly 70%. In addition, providing the inner shafts of the roller bearings with a built-in synchronizing mechanism results in reduced size and weight.

Minute dimples were created on the piston skirt by a special surface treatment. As a result, oil film sustainability between the pistons and cylinders is enhanced, enabling a roughly 30% reduction in friction with low viscosity engine oil.

The use of these techniques has achieved at least 10% less friction in the new engine than that in a conventional 1.0-l class engine.

### 5.4. Weight reduction

The construction and materials of nearly all the components of the engine were reviewed with the objective of creating the world's lightest 1.0-l class engine.

The carbonized connecting rod used in the S2000 was also adopted. Its carbonizing cementation greatly improved strength at higher engine speeds. The application of this strength-enhancing treatment, combined with a slimmer design, reduced the connecting rod weight by roughly 30% when compared with conventional connecting rods.

Oil pans are usually constructed from sheet steel or aluminum alloy. Magnesium generally suffers from a considerable decrease in creep strength at 120°C and above and thus has insufficient resistance to engine oil at high temperatures. Honda improved the creep strength limit to 150°C, enabling magnesium material to be used for the oil pan. Countermeasures against galvanic corrosion are applied by using steel bolts with aluminum washers. The weight of this magnesium oil pan is about 35% less than a comparable aluminum pan, the weight being reduced in nearly the same ratio as that of the specific gravity.

Flexible plastic materials are used for the intake manifold, cylinder head covers, water pump pulley and other intake system components.

The dry weight of the engine alone is less than 60 kg, making it the lightest engine in the world in the 1.0-l class.

### 5.5. Exhaust gas emission

Both leaner combustion and a $NO_x$ adsorbing exhaust catalyst were applied to reduce the levels of $NO_x$ while obtaining a high level of thermal efficiency. The exhaust manifold was integrated with the cylinder head and an $NO_x$ adsorbing catalyst for the special lean-burn combustion system were newly developed.

#### 5.5.1. Exhaust manifold-integrated cylinder head

In a conventional engine, separate exhaust ports are provided for each cylinder within the cylinder head and an external exhaust manifold links those exhaust ports into a single pipe that discharges the exhaust gases through the catalytic converter. In this newly developed cylinder head, however, the exhaust ports converge into a single port within the cylinder head, as shown in Fig. 5. In addition to significantly reducing weight, this design also results in a reduction in the surface area over which heat is dissipated, which decreases the heat lost from the exhaust gas and enables faster activation of the catalyst.

*5.5.2. $NO_x$ adsorption reduction three-way catalyst [4]*

A catalyst was developed which absorbs $NO_x$ on the surface and has a high durability to high temperature. Although $NO_x$ emission levels are less with lean-burn combustion, the exhaust gas contains a relatively high level of oxygen that inhibits the reduction of $NO_x$ when an ordinary three-way catalyst is used. In contrast, this new catalyst is able to adsorb $NO_x$ under lean-burn combustion conditions. The adsorbed $NO_x$ is released and reduced while operating at the theoretical air-fuel ratio and discharged into the exhaust as $N_2$. This adsorbing catalyst enables $NO_x$ emission levels under lean-burn combustion conditions to be reduced to 1/10 of the level with a conventional three-way catalyst. However, it should be noted that $NO_x$ adsorption is severely impacted by sulfur; thus, this level of efficiency requires use of very low sulfur fuel.

The use of this new adsorbing catalyst allows lean-burn combustion to be maintained while reducing $NO_x$ emissions, thereby ensuring low fuel consumption.

These actions enable the emission levels to be reduced to one-half the post-53 exhaust gas emission standards for CO, HC and $NO_x$. In addition, this engine also conforms to the Ultra-low Emission Vehicle (ULEV) regulations of the state of California, U.S.A., and is compatible with other emissions regulations throughout the world.

## 6. Body design

In addition to helping to achieve the fuel consumption targets, the following development objectives were set for the body to satisfy basic vehicle requirements and to hold the vehicle cost down to a practical level:

- A 50% reduction in the body weight versus the 3-door Civic.
- High body rigidity.
- High collision safety.
- Low number of parts.

The aluminum body of the NSX developed in 1990 was about 40% lighter than the steel body equivalent, while maintaining the monocoque construction normally used in a steel body. However, this resulted in increased production tact time, plus a large number of parts and welds due to limitations on the press-formability and weldability of the aluminum components.

An aluminum space-frame construction using extended aluminum material has recently begun to be used. This allows greater use of the properties of aluminum, in comparison with monocoque construction, making it possible to achieve lighter weight and higher rigidity. The result of in-depth studies, however, showed that space-frame construction would require fasteners for attaching the outer panels and various other functional parts. It was ultimately determined that the target productivity could not be achieved.

### *6.1. Hybrid aluminum body construction*

We therefore developed a hybrid aluminum body construction that combines the advantages of both monocoque and space-frame construction. It takes full advantage of the properties of aluminum and optimally combines the three forming methods of pressing, extrusion molding and casting to achieve outstanding rigidity and collision safety, while satisfying the requirements of low cost and high productivity. This hybrid body concept is based on the following principles:

- Increasing the application of extrusion-molded parts, which allow the forming of complex shapes to provide adequate strength and rigidity with minimum weight.
- Using cast parts for joints to improve joint rigidity and to centralize part mounting and other functions for fewer parts.
- Minimizing the application of press-formed parts to increase productivity.

The places where each type of forming method for the aluminum material is used are shown in Fig. 6. As can be seen in the figure, the frame is either straight or smoothly curved with an extremely low curvature. Frame members are connected with high efficiency using castings with uniform functions and direct coupling capability. The resulting structure distributes the suspension loads and collision energy throughout the entire frame.

The use of extruded members and cast parts allowed the number of parts to be reduced by approximately 15% and the number of welds to be reduced by approximately 24%, when compared with the aluminum monocoque body of the NSX. Moreover, the weight of the body-in-white is approximately 47% less than the 3-door Civic.

### *6.2. Body rigidity and collision safety*

*6.2.1. Body rigidity*

Since the Young's modulus for aluminum is roughly only one-third that of steel, the cross-sectional thickness of extruded members was increased in the region of higher energy input to ensure adequate rigidity of the frame members. This extruded-member frame is connected with high rigidity by ensuring an adequate amount of overlap with the cast connectors, making it possible to achieve a lightweight aluminum body with high rigidity comparable to that of a well-designed steel body.

*6.2.2. Collision safety*

Polygonal-rib-structured cross-sections are used for the collision energy absorbing members at the ends of the

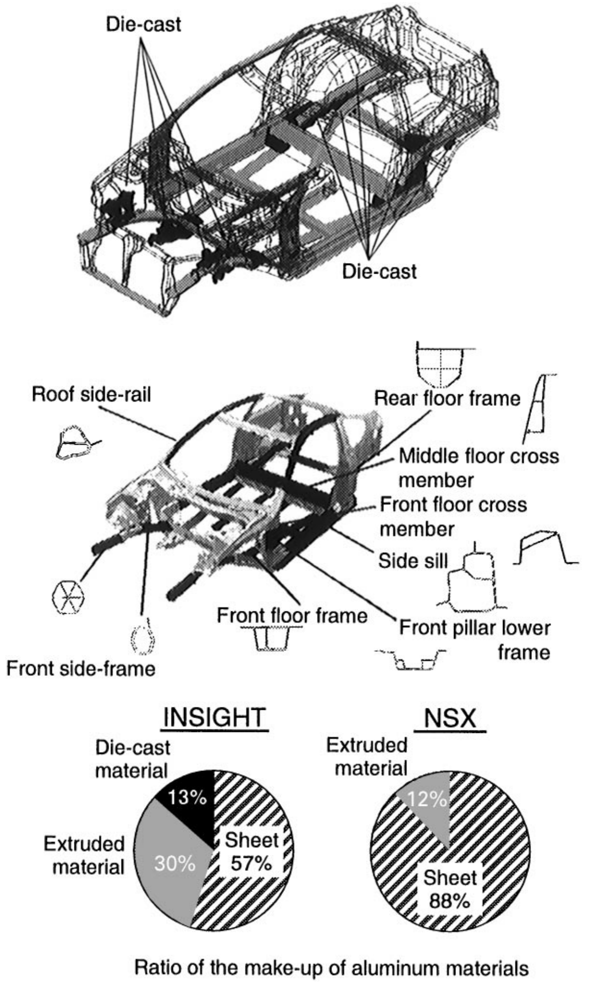


Fig. 6. Aluminum hybrid body of INSIGHT.

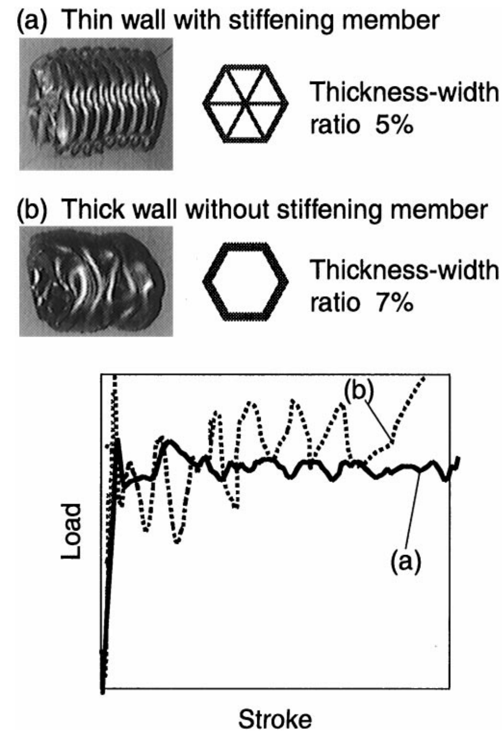


Fig. 7. Effect of stiffening member.

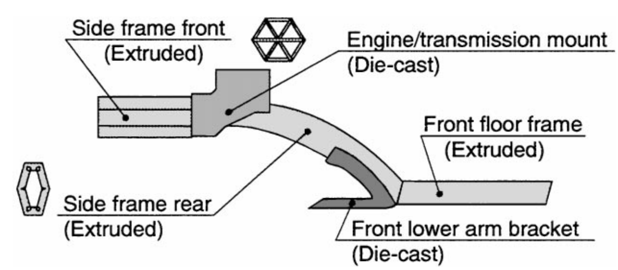


Fig. 8. Construction of front side frame.

side frames and rear frame to take advantage of the characteristics of extruded aluminum members. Based on the relationship between the mean stress of a rectangular plate and the ratio of the sheet thickness to width [5], cross-sections were provided to absorb energy during a collision by stable compression and collapse as shown in Fig. 7.

The use of this construction method in areas such as the ends of the side frames made it possible to obtain a 50% increase in the amount of energy absorbed and a 37% reduction in weight relative to a steel body.

For protection in a head-on collision, the side frames were divided into front and rear sections. As shown in Fig. 8, different extruded members in the front and rear sections are coupled with castings so that the front sections compress and collapse in a stable manner, while the rear sections are curved to obviate penetration and impact with the chassis.

The frame cross-sections were selected based on the same concept as for a rear end collision, resulting in increased energy absorption efficiency and a significant reduction in weight.

The above-mentioned body construction was determined to satisfy high-level, in-house safety standards, including the head-on 40% offset crash test at 64 km/h and the head-on full lap crash test at 55 km/h. These standards exceed the regulated crash test speeds of the U.S., Europe and Japan, while resulting in a significantly lower weight.

## 7. Air resistance reduction

We attempted to achieve the ideal shape for aerodynamic efficiency in order to reduce drag.

A long body is generally considered to be advantageous for aerodynamic performance. However, smooth air flow from the front to the rear along the sides of the vehicle is important for obtaining high aerodynamic performance with a compact body. With this in mind, the rear tread was made narrower than the front to guide the air flow to the rear sides, as shown in Fig. 9. In addition, the shape of the roof received special attention to ensure

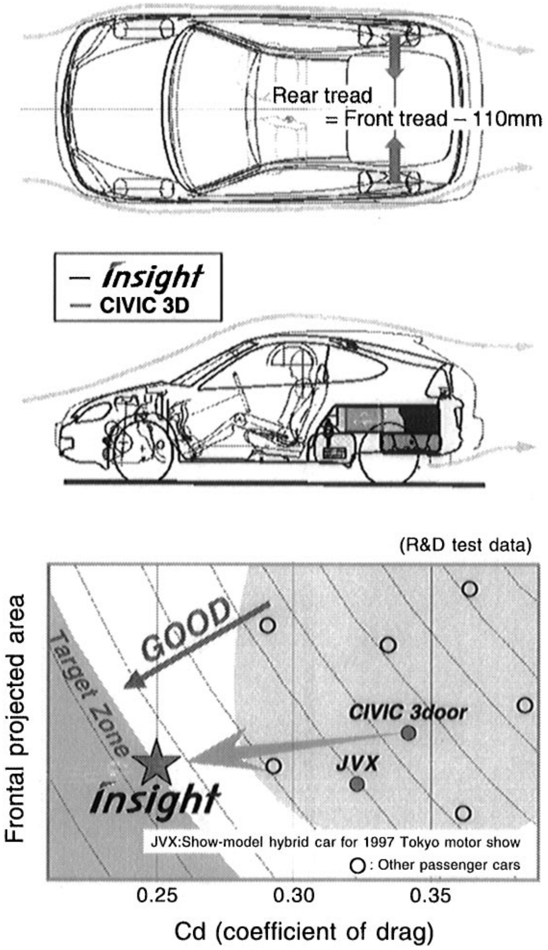


Fig. 9. Aerodynamic characteristics.

good air flow over the top of the body and the projected front surface area was also made as small as possible to reduce the air resistance.

The shape of the front fenders was also optimized and rear wheel skirts were incorporated to allow air to flow smoothly along the body and minimize tire air resistance. The entire under body was given a flat contour to enhance the flow-straightening effect.

The result is an extremely high level of aerodynamic efficiency for a mass-produced vehicle, especially one this short, achieving a Cd value of 0.25 as shown in Fig. 9.

## 8. Other technological features

### 8.1. Tires and wheels

A new tire compound was developed to reduce rolling resistance to roughly 40% below that of conventional tires of the same size, while still ensuring wet-surface performance. The result is a fuel consumption reduction in the order of 4% in the Japanese 10–15 mode.

The cast aluminum wheels are approximately 40% lighter than conventional aluminum wheels of the same size, and the aerodynamic dish type design has also reduced air resistance.

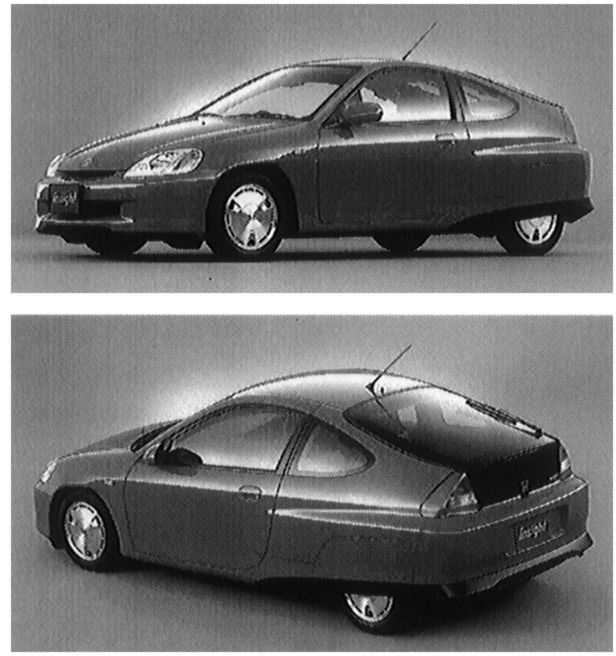

Fig. 10. Appearance of the HONDA INSIGHT.

### 8.2. Chassis weight reduction

A simple suspension system, with aluminum casting knuckles and lower arms, and hollow strut damper rods, was employed to reduce weight. Aluminum is also used for the brake pedal, and for the clutch pedal with manual-transmission vehicles. The fuel tank is made of high-density polyethylene and the footrest in the automatic transmission vehicles is also made of plastic.

These result in the weight of the entire chassis being approximately 80 kg lighter than that of the Civic.

### 8.3. Reduction of weight and power demand in steering system

Fuel consumption was also reduced by using compact, lightweight pinion-type electric power steering system with low power demand. A lightweight magnesium alloy steering wheel is also fitted.

## 9. Conclusion

We devised a new concept for a hybrid power train to achieve the lowest fuel consumption of comparable cars in the world. This was accomplished by careful attention to the design of power train components, body, chassis and numerous other components.

The target fuel consumption of 35 km/l was achieved with vehicle performance comparable to that of a 1.5-l engine. Low emission levels equivalent to one-half the levels of the post-53 exhaust gas emission standards were concurrently achieved.

Styling is based on a shape with outstanding aerodynamic performance, leading to an image that is both futuristic and dynamic, as shown in Fig. 10. Attention was also given to recycling capability, collision safety and driveability from an ultra-low fuel consumption hybrid car.

This development project involved the generous cooperation of numerous personnel, to whom the authors take this opportunity to express their deep appreciation.

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