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Development of aerodynamics for a solar race car

Hiroyuki Ozawa[a], Sumio Nishikawa[a], Dai Higashida[b]

[a] *Honda R&D Co., Ltd, Tochigi R&D Center, Shimotakanezawa 4630, Haga-machi, Haga-gun, Tochigi, 321-3393 Japan*
[b] *Honda R&D Co., Ltd., Wako R&D Center, Chuou 1-4-1, Wako-shi, Saitama, 351-0193 Japan*

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Abstract

The dominant factor of a solar car is running resistance, especially aerodynamic drag; and the reduction of the C_D (drag coefficient) × A (frontal projected area) value is a crucial task to maximize the performance of a solar car. This paper will introduce the aerodynamic approach of the '96 Honda solar car which participated in the World Solar Challenge, the world's top solar car race.

1. Introduction

To alleviate environmental problems, research and development is conducted throughout the world on automobiles that run on new energies. Promising new technologies for the future are automobiles like the solar cars that effectively utilize solar energy with solar cells. This paper reports on the aerodynamic development of the Honda '96 "Dream" that participated in the World Solar Challenge, the largest solar car race in the world. This race, well-known for its 3000 km long distance course, is held every three years in Australia.

2. Contribution of aerodynamic properties of solar cars to overall performance

Solar cars have a smaller amount of energy available compared to conventional, internal combustion engine passenger vehicles, and therefore, solar car aerodynamic drag must be reduced to a very low level in order to have the same performance as conventional vehicles. As a result of aerodynamic development, the Honda '96 "Dream" solar car requires only 1.62 kW (2.2 PS) to cruise at 100 km/h, while a conventional vehicle with a C_D (drag coefficient) value of 0.32 requires as much as 13.52 kW (18.4 PS), as shown in Fig. 1. In other words, only 12% of the driving force for conventional vehicles is sufficient for the solar car.

"Speed", of course, is the most important performance factor in a race, and has to be increased. The balance between electric energy generated from solar cells and energy consumption, dictated in part by the running resistance, determines the cruising speed of a solar car. This therefore means that a higher output and/or higher efficiency motor, with a larger generating capacity, and smaller running resistance will result in a higher cruising speed. Among these factors, reduction in running resistance would be the most effective method as long as the efficiency of the solar cells remain at the same level, because regulations of the solar car race require the body size of a participating solar car to be 6 m long or less, 2 m wide or less, and between 1 and 1.6 m high, thereby limiting the total area of solar cells installed on the body. Running resistance consists of rolling resistance dictated by weight and tire factors and aerodynamic drag resulting from the body shape. The World Solar Challenge course does not require much acceleration nor deceleration, and most of the time, participating solar cars cruise at a constant speed. Aerodynamic drag affects the vehicle performance for more than rolling resistance, because, at approximately 300 kg, vehicles are lightweight. Fig. 1 shows the driving force required to cruise at a constant speed as a function of aerodynamic drag. For example, the ratio of aerodynamic drag to rolling resistance, both contributing to the total running resistance, is 4 : 1 at a speed of 100 km/h. The contribution of aerodynamic drag increases even further above 100 km/h, because

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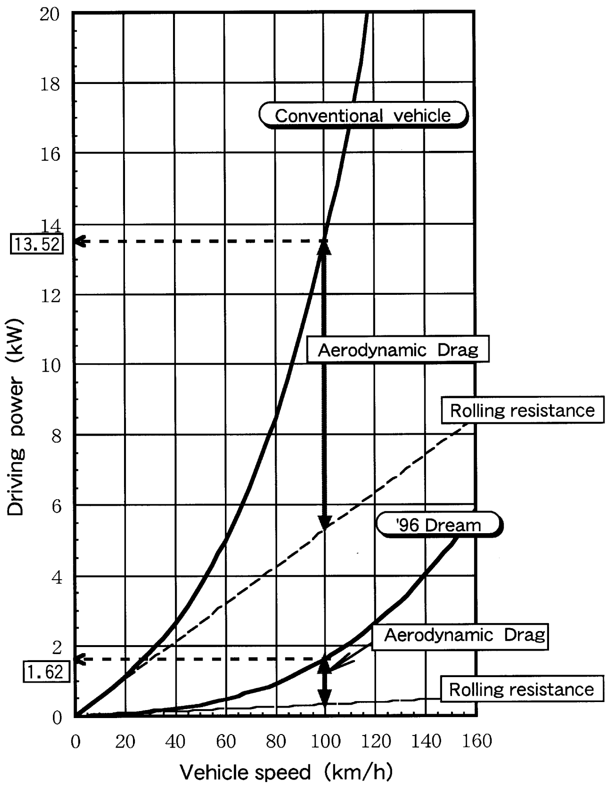


Fig. 1. Driving power of '96 Dream and a conventional vehicle.

aerodynamic drag increases proportional to the square of speed.

This is sensibility analysis considering the generating capacity, surface conditions and gradient of the race course reveals that a 10% reduction in aerodynamic drag would result in a 2.5 km/h increase in the daily average speed and a 20 km increase in the daily running distance. Thus, aerodynamic design would have a significant impact on the vehicle performance, and an aerodynamic designer would have to optimize aerodynamic performance by reducing the C_D to the 0.001 order.

3. Development of "Dream", a solar car

The body of a solar car should be designed to optimize the balance of the generating capacity of solar cells and aerodynamic performance in order to have the highest overall efficiency.

Generating capacity will be increased by:

1. Improving the generation efficiency of solar cells;
2. Increasing the area of solar cells installed on the body;
3. Shaping the vehicle body to allow solar cells to receive more solar energy.

The highest aerodynamic performance will be pursued under the above-mentioned restrictions.

3.1. Aerodynamic development of Honda '96 "Dream"

3.1.1. Concept of Honda '96 "Dream" body

Driving performance was improved based on experience gained from the previous two races. Safety was also pursued in developing Honda '96 "Dream" and the body was reshaped for easier driving. We set a target to break the course record with the '96 "Dream."

The following three areas were mainly worked out (see also [1]):

(1) *Increase in generation capacity*: The '96 model would have 20% more in a projected area for solar cells compared to the previous '93 model, which had a projected area of 8 m^2, exploiting the race regulation that allowed to install solar cells on the total body surface if the vehicle accommodates two passengers.

(2) *Safety*: (1) Predictive and preventive safety (forward and side visibility): A canopy was employed to allow the driver to have more visual information input (improvement in visibility). (2) Driving safety (conversion from a three-wheeled to four-wheeled vehicle): The four-wheel configuration and front and rear double wishbone suspensions were employed for straightline stability at high speeds and increased toughness against external disturbances, as the average speed exceeded 100 km/h in some sections in the '93 World Solar Challenge race. (3) Collision safety (passenger protection): A crushable zone to absorb a collision impact was secured to protect the driver legs in a small accident while in urban areas. Driver and passenger seats were configured back to back so that one protective roll cage would protect both passengers.

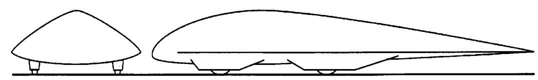
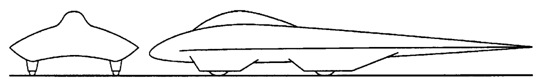
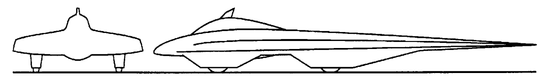
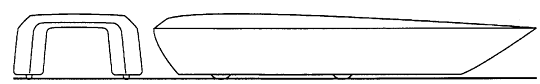
(3) *Reduction in running resistance*: An aerodynamic body, achieving stable driving, with very small aerodynamic drag was developed to allow the balance of the above safety requirements at a high level.

3.1.2. Body development for the '96 "Dream"

The body of the '96 model was developed to have a lower aerodynamic drag with a generating capacity and safety performance of the '96 model surpassing those of '93 model. Aerodynamic stability was also incorporated as much as possible in terms of lift and yaw moment. One-sixth scale models of three basic '96 model types were fabricated and tested after preliminary examination was conducted on the modified '93 model. Table 1 shows the results for the basic models. The body was designed like a cross section of a laminar airfoil to minimize the frontal projected area, A, as well as the C_D value to have the lowest possible aerodynamic drag ($C_D \times A$). As a result, the type B body (shown in Table 1) was selected and was then refined to further reduce aerodynamic drag.

The body was refined in wind tunnel tests with $\frac{1}{6}$ scale clay models. Reynolds number was approximately 3×10^6, and change in air speed (change in Reynolds

Table 1
Study of basic shapes

	Basic shapes	$C_D \times A$
A	The four–wheel, modified '93 Dream $A = 1.064\ m^2$ 	0.126
B	The laminar flow airfoil image type 1 $A = 0.952\ m^2$ 	0.108
C	The laminar flow airfoil image type 2 $A = 0.947\ m^2$ 	0.119
D	The type focusing on generated output $A = 1.095\ m^2$ 	0.185

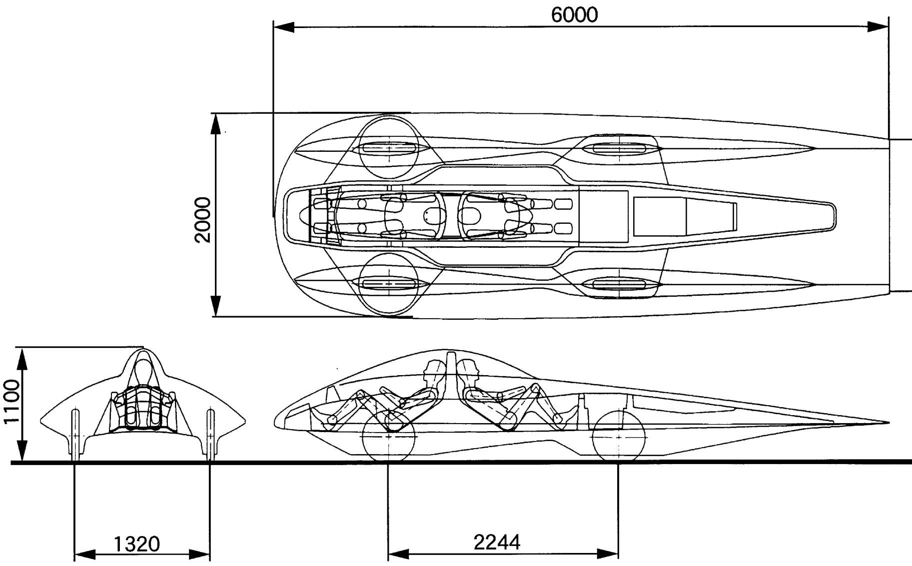


Fig. 2. '96 Dream final dimensions.

number) did not affect the values of aerodynamic performance. The design was finalized for the '96 model with scale models, because time constraints made it impossible to have tests on full size models. As a result, accuracy in the model tests, particularly precision in body shape, was extremely important. Even the model surface finishing would have a large effect on the aerodynamic performance measurement after the C_D of the body became extremely low at approximately 0.10. Therefore, a specially assigned model technician shaped and finished the models and the aerodynamic performance of each model was carefully measured. The shape of the final $\frac{1}{6}$ scale model version was then precisely measured and the dimensions for the '96 model were calculated. Fig. 2 shows the shape and size of the '96 model.

3.1.3. Refinement in body shape

Fig. 3 shows the parts that were refined after the selection of the basic body shape.

3.1.3.1. Rear body. Horizontal narrowing at the rear end of the body will lead to a smaller C_D value. The previous

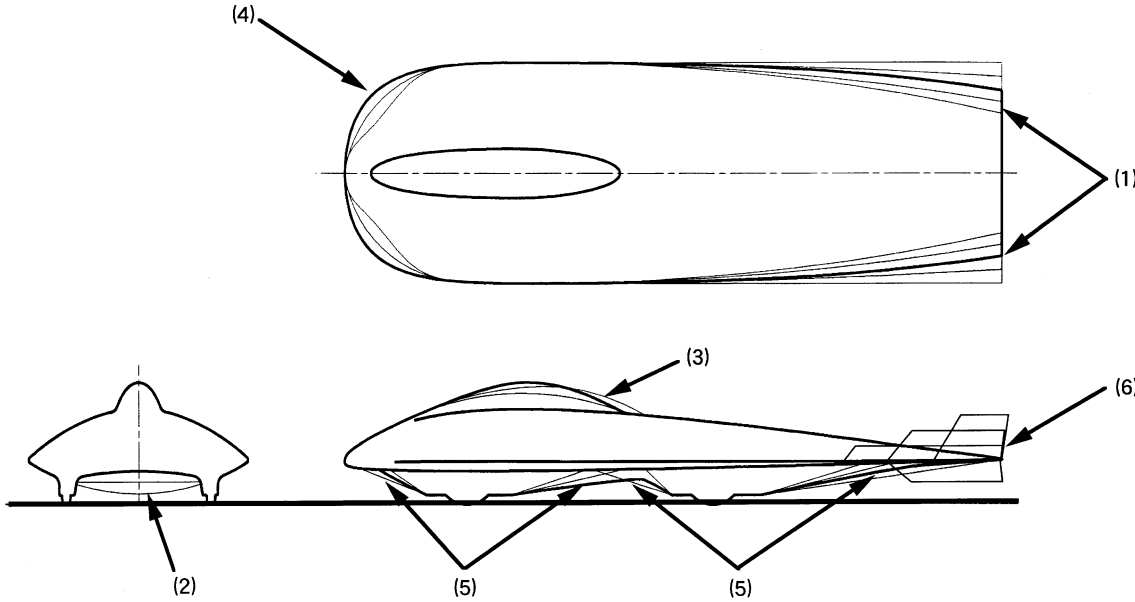


Fig. 3. '96 model shape detail study.

'90 and '93 models had only a 100 mm contraction at each side of the rear end of the body to ensure for a sufficient solar cell area and generating capacity. A much larger area was available for solar cells on the '96 model compared to the '90 and '93 models, and it was decided that more narrowing, 250 mm, at each side of the rear end of the body to reduce the C_D value would produce a better overall performance.

3.1.3.2. Floor. Concave flooring was employed to minimize the frontal projected area. The floor shape was optimized, avoiding an increase in C_D and ensuring an appropriate driving position.

3.1.3.3. Canopy. (1) Driver and co-driver seats were configured back to back to minimize the canopy area, thus maximizing their available area for solar cells. (2) The canopy shape was determined to ensure an appropriate view, as well as an appropriate driving position for the driver, while minimizing the aerodynamic drag and frontal projected area of the canopy.

3.1.3.4. Front body. Front body shape was optimized using surfaces whose curvature was large enough for solar cells to be installed on, because the upper surface of the entire '96 model body was available for solar cells. The model surface finishing would have a significant effect on the aerodynamic performance measurement through frictional resistance. Therefore, models were carefully shaped and finished before any aerodynamic performance was measured.

3.1.3.5. Wheel cover. It was important to ensure that the floor shape around the wheels was formed by continuous and smooth curved surfaces. The four-wheeled '96 model was expected to have better aerodynamic performance, compared to the three-wheeled '93 model, in terms of frontal projected area because the front and rear wheels were aligned. Examination of a number of shapes, shown in Fig. 3, led to the installation of covers around the wheels in order to have a continued, smooth surface from the floor to the cover in a longitudinal direction. Covers for the front wheels turn along with the wheels. The same mechanism employed in the '93 model was again employed for the '96 model, which ensures a minimum clearance between the wheel and cover at the opening on the cover bottom.

3.1.3.6. Aerodynamic stability. Aerodynamic stability was also examined and a stabilizing wing was planned to be installed on the rear body in order to improve driving stability while experiencing strong side winds, and its aerodynamic effects were measured. It was found, however, that the wing also had some negative effects, such as increased aerodynamic drag and a decreased generating capacity because of its shade. It was finally decided not to employ the stabilizing wing because tests using the final version of the '96 model revealed that the vehicle was stable without the wing.

3.1.3.7. Others (vehicle tests). Measurement for the total pressure loss and flow visualization using tuft grids were conducted in a wind tunnel with 3.6% blockage ratio. As a result, it was confirmed that the major causes of flow disturbances were the canopy and the wheel covers (Fig. 4), and no major air disturbances occurred in other areas. Major differences in aerodynamic performance between $\frac{1}{6}$ scale models and the actual vehicle resulted from the clearance between the wheel and wheel cover. The clearance was reduced to an absolute minimum by carefully determining the wheel displacement, but it still increased C_D by approximately 0.01. Surface roughness of solar panels, or modules that consists of solar cells, had a considerable effect on aerodynamic drag. These effects were suppressed as much as possible for the race vehicle.

3.1.3.8. Computational fluid dynamics analysis. Shape and structure of the upper body cowl were designed based on the computational fluid dynamics (CFD) analysis of pressure (C_p) distribution on the surface, as shown in Fig. 5. The total number of meshes used for the calculation was approximately 850 000, and reinforcement members were also incorporated based on this analysis. In this analysis, the flow field surrounding the solar car was assumed to be a transient, incompressible viscous fluid governed by the continuity and the Navier–Stokes equations. The aerodynamic simulation system solved the controlling equations by the Marker-and-Cell (MAC) method while applying the Kawamura Scheme, a third-order upwind scheme, to convection terms in the Navier–Stokes equations.

4. Future development issues

4.1. Effects of speed

Suspension with spring constants similar to conventional passenger vehicles were employed for the '96 "Dream", contributing to soft ride comfort. As shown in Fig. 6, however, soft suspension resulted also in lower aerodynamic performance at high speed, because the lifting force would change the vehicle position. The overall body shape was designed like the cross section of an airplane wing, resulting in a large C_{Lf} (front lift coefficient). The front part of the body would therefore receive more upward force at a higher speed. These was a noticeable effect on the aerodynamic performance at a speed of 120 km/h or higher in wind tunnel tests. The degradation effect on aerodynamic performance was neglected for the

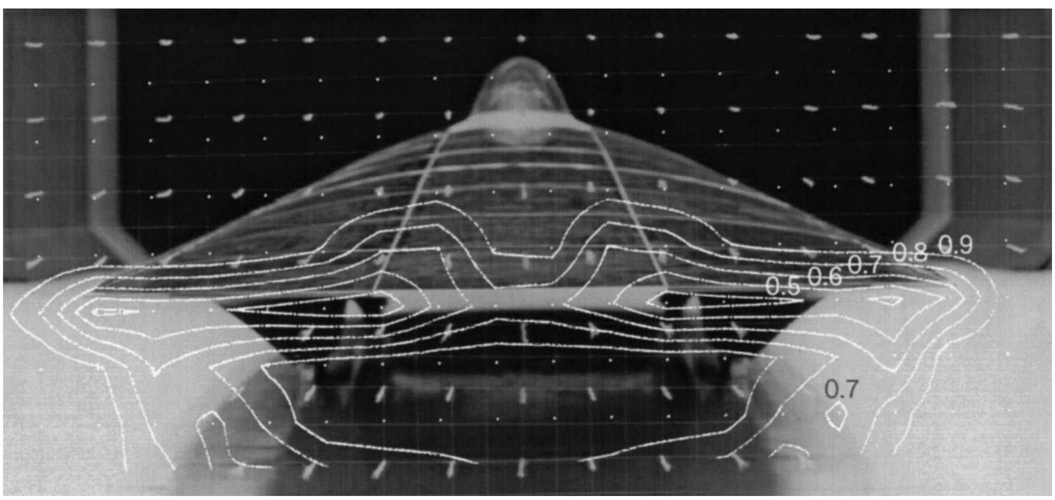


Fig. 4. Total pressure loss and flow visualization with tuft grid.

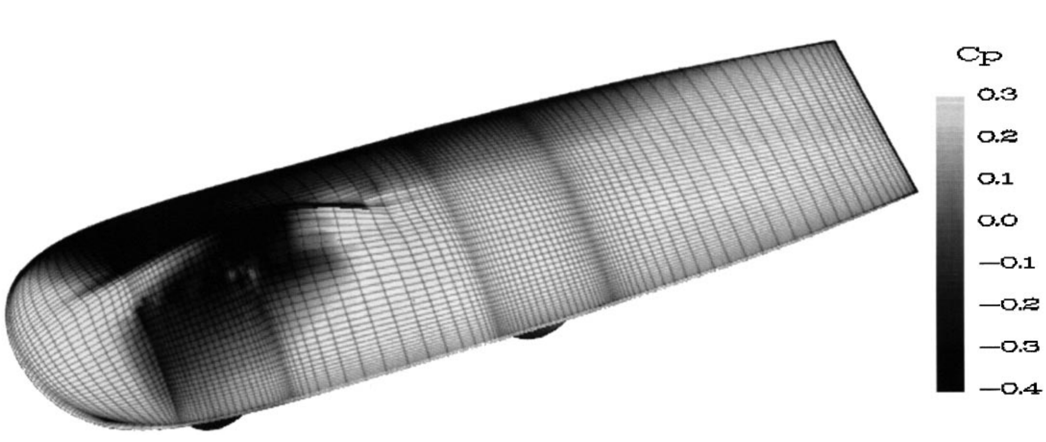


Fig. 5. Pressure distribution on the surface.

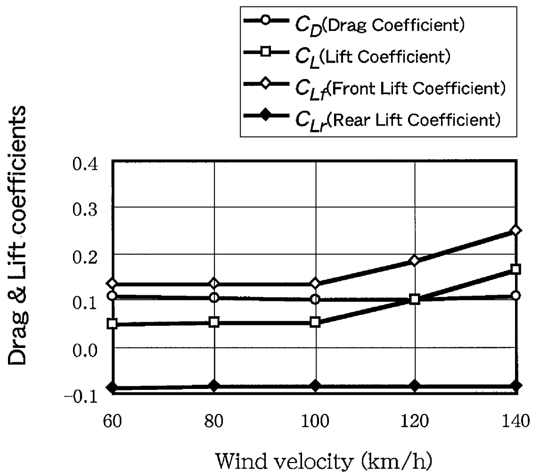


Fig. 6. Drag & Lift coefficients with respect to wind speed.

non-final session of the race due to the fact that the target cruising speed set was 100 km/h. However, the front was lowered by approximately 0.4° in the qualifying session to suppress C_{Lf} increase, in order to achieve the highest possible speed.

Future research and development will be required to refine the suspension and/or front lift coefficient in order to further increase the cruising speed.

4.2. Effects of crosswind (disturbances)

A solar car on the road has to run through natural wind and thus receives its disturbances. The '96 "Dream" was thought to be prone to crosswind disturbances because it was considered lightweight, at approximately 300 kg, with a relatively large body. Fig. 7 shows the crosswind sensibility of the '96 "Dream" measured in wind tunnel tests. It can be seen from the figure that increasing the yaw angle from 0° to 12° (corresponding to receiving side wind of 6 m/s from the lateral direction, while running at 100 km/h) reduces front and rear wheel load by approximately 2.1 and 21.4 kg, respectively. The reduction cannot be neglected because it translates into a 1.4% and 14.2% reduction in front and rear wheel load, respectively. Disturbances induced on vehicle behaviour by lift force resulting from crosswind, as well as other disturbances by side force and yaw moment, must be suppressed to a level low enough not to disturb vehicle driving.

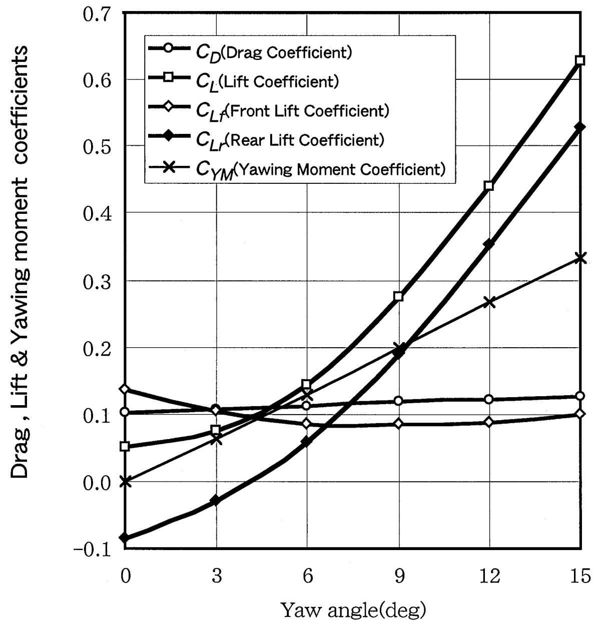


Fig. 7. Drag & Lift coefficients with respect to yaw angle.

Fig. 8. '96 "Dream" winning the World Solar Challenge Race.

5. Summary

The '96 "Dream" won with a new course record at the fourth World Solar Challenge held from late October through early November, 1996. The target performance was also achieved with the aerodynamic performance of the '96 "Dream" improving over the '93 "Dream" by 11% in terms of $C_D \times A$. Refining body shape around wheels and surface finish further improved the aerodynamic performance of the body that already had a very low aerodynamic drag.

Body shape specifically designed for one-directional air flow may not result in the best overall performance because a vehicle receives complicated aerodynamic force and moment influences, which can be separated into the six components. The development target of the '96 "Dream" was mainly to reduce aerodynamic drag, and further optimization in terms of disturbances is necessary. Future aerodynamic development will be required to take these elements into account, as vehicle speed will be higher in future races. We would like to conduct research and development of commercial solar

Table 2
Honda solar cars "Dream" specification

	'90 Model	'93 Model	'96 Model
Aerodynamic drag ($C_D \times A$)	0.134	0.114	0.101
Drag coefficient (C_D)	0.120	0.100	0.101
Frontal area A(m^2)	1.116	1.140	0.999
Solar cell area (m^2)	7.752	8.278	9.980
Rated power (motor) (W)	1200	1500	1500
Speed (max.) (km/h) (Cal.)	120	130	160
Speed (ave.) (km/h) (Cal.)	68	86	95
Length (mm)	5743	5975	6000
Width (mm)	1998	2000	2000
Height (mm)	1054	1020	1100
Wheelbase (mm)	2375	2250	2244
Track (mm)	1400	1340	1320
Total weight (kg)	218	267.5	330

cars as well as racing vehicles, and we hope that solar cars become commercialized in the near future.

Fig. 8 shows '96 "Dream" winning the World Solar Challenge race. Getting the pole position with a new course record of a maximum speed of 135.34 km/h, running the race distance of 3010 km for 33 h and 32 min, and rewriting the average time record to 89.76 km/h, "Dream" has achieved two consecutive victories from 1993.

Table 2 shows Honda solar cars "Dream" specification since 1990.

References

[1] Ozawa, H. et al., Aerodynamic development of solar cars (in Japanese with English summary), Proceedings of Spring Convention, No. 9731514 (1997).