

Aerodynamics Development for Bonneville Race Car Using Fluid Simulation

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ABSTRACT

Honda participated in both Bonneville Speed Week, held in August 2016, and Mike Cook's Bonneville Shootout, held in September 2016, at Bonneville Salt Flats near Salt Lake City, Utah (USA) using a special vehicle equipped with a 658 cm³ displacement engine for a Kei car, which is an original Japanese vehicle category. Fluid simulation was used to perform aerodynamics development for the race car to create a body shape with aerodynamic drag that enables to achieve the target speed with limited engine power and to secure driving stability. The goal was to achieve a speed of 450 km/h, which would be a new speed record for the participation category. A body shape with the target drag was designed using a prototype model, and models of record holders, as references. Vertical and horizontal wings were attached to the race car to suppress vehicle spin and flipping, in addition to increasing driving stability at high speeds. On site, it became necessary to change the shape for increased visibility while driving, but the developed process allowed for a rapid body shape change, keeping vehicle stability in consideration. As a result, the official world speed record of 421 km/h in the Category A, Group 1, Class 4 was set at Mike Cook's Bonneville Shootout (International Automobile Federation World Land Speed Records).

1. Introduction

Honda challenged the Bonneville Speed Week held in August 2016 at the Bonneville Salt Flats near Salt Lake City, Utah (U.S.A.) using a race car consisting of a special body equipped with an engine having the same displacement as that of a Kei car, which is an original Japanese vehicle category.

The top speed set for this participation category was 433.686 km/h (269.480 mph) recorded by team Costella Yacoucci during the August 2007 Bonneville Speed Week. Therefore, race car development was performed with a target speed of 450 km/h, which would be a new world speed record in this category.

The dominant vehicle running resistance when driving at high speeds is aerodynamic drag, so a target drag was set with the body shape designed to achieve the target speed with limited engine power.

The Bonneville Salt Flats used for the race venue are located to the west of Salt Lake City, Utah (U.S.A.), and are vast salt plain highlands covering some 260 km² at an elevation of approximately 1,200 m. Mountains rise to the northwest of the course location, measured in the 2,000 m class, and gusty winds are known to blow down from them.

Investigation of past races revealed cases where cars

spun and crashed while driving. The causes of these incidents were investigated, and it was found that although the event organizers level the course track surface during the event period, the track surface condition easily changes between states ranging from watery sherbet to free-flowing sand, etc. Furthermore, the track surface gradually becomes rougher as the races proceed, with rutting and level differences occurring in some places.

To hit the target speed, it is important to achieve the target drag and to secure vehicle stability so that disturbances such as wind or road surface inputs do not produce spinning or flipping. Therefore, fluid simulations were used to design a body shape for the target drag, performing aerodynamics development for the race car with the goal of securing vehicle stability in consideration of the driving environment.

As a result of participating in Bonneville Speed Week, although the target speed was not achieved, Honda was invited by the organizers to participate in Mike Cook's Bonneville Shootout (International Automobile Federation (FIA) World Land Speed Records) held in September, successfully setting the official world speed record then and there at 421 km/h in the Category A, Group 1, Class 4.

This report examines the race car aerodynamics development using fluid simulation.

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Table 1 Bonneville Speed Week of participation category

Body	BFS class (Blown Fuel Streamliner)	Turbochargers, superchargers and any choice of fuel are allowed in streamliner car
Engine	J class	508-753 cm ³

Table 2 Specifications of Honda S-Dream Streamliner

Body	Car name	Honda S-Dream Streamliner
	Length	8,500 mm
	Width	840 mm
	Height	1,185 mm
	Vehicle weight	830 kg
	Wheel base	4,800 mm
	Tire size (front, rear)	125/60R15, 115/110R15
Engine	Displacement	658 cm ³
	Bore × Stroke	66.0 × 64.0 (mm)
	Power	184 kW (250 PS)/10,000 rpm
	Torque	200 Nm (20.4 kgf.m)/9,000 rpm
	Cooling system	Water RAD, I/C
	Turbocharger	Garrett

2. Participation Category and Vehicle Specifications

2.1. Participation Category and Regulations

At Bonneville Speed Week, Honda participated in the category of special cars equipped with supercharged Otto-cycle engines containing a displacement of 508 to 753 cm³⁽¹⁾. Table 1 shows the participation category.

The flying start method of pushing the race car from behind with another car was selected as the starting method.

2.2. Vehicle Specifications

A special Bonneville race car equipped with an engine displacement of 658 cm³ and a power of 184 kW was developed in accordance with the SCTA official rulebook⁽¹⁾ in order to qualify for participation. This race car was named the Honda S-Dream Streamliner.

Table 2 shows the specifications and Fig. 1 shows the appearance of the vehicle.



Fig. 1 Appearance of Honda S-Dream Streamliner

3. Aerodynamic Performance Design

Aerodynamic performance requirements that would enable to achieve the target speed and stability were set and vehicle development was performed on the assumption of the mounted engine power.

3.1. Body Drag

Vehicle traction force and running resistance have an equilibrium relationship during driving, so to achieve the target speed of 450 km/h with limited engine power, it is necessary to reduce the running resistance (rolling resistance and drag) at the target speed to less than traction force.

Drag D is produced by uneven shapes such as the body exterior shape and protrusions, air flows entering and exiting the body, and friction between the body surface and the surrounding air. Drag increases proportionately to the square of vehicle velocity as shown in Eq. (1), so it becomes dominant during high-speed driving.

$$D = \frac{1}{2} \rho v^2 CDA \quad (1)$$

Here, ρ is the air density, v is the vehicle velocity, CD is the drag coefficient, and A is the frontal projected area of the body.

Therefore, to achieve the target speed of 450 km/h with 184 kW engine power, the target drag excluding rolling resistance was set to $CDA \leq 0.09$ (Fig. 2).

3.2. Lift Suppression

The target speed for this vehicle is at the level of, or greater than, aircraft takeoff speed, so it is necessary to generate negative lift (downforce) on the body to enable driving without the vehicle separating from the ground. Therefore, the lift coefficient (CL) target was set to < 0 .

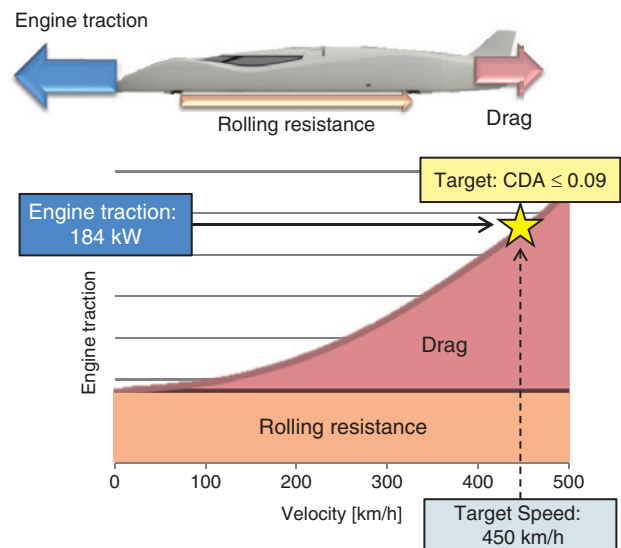


Fig. 2 Relationship between engine traction and total resistance

3.3. Spin Suppression

Disturbances such as vehicle vibration due to road surface unevenness, unexpected cross winds, and gusty winds may produce the spin phenomenon where the vehicle turns excessively. For this reason it is necessary to provide stability that will enable the vehicle to travel straight even when disturbances occur.

It is known that when a vehicle travels at high speeds, the aerodynamic characteristics of the lateral force and the yawing moment relative to the lift acting on the front and rear wheels and the yaw angle contribute to vehicle stability. In the range of a small body slip angle when travelling in nearly a straight line, these characteristics can be assessed using the stability factor, which is an indicator of the dynamic characteristics of the vehicle^{(2), (3)}.

Equation (2) shows the equation for calculating the stability factor A_{aero} in consideration of aerodynamic characteristics as shown in Fig. 3.

$$A_{aero} = -\frac{m}{2l^2} \frac{l_f(K_f + \Delta K_{aero_f}) - l_r(K_r + \Delta K_{aero_r})}{(K_f + \Delta K_{aero_f})(K_r + \Delta K_{aero_r})} \quad (2)$$

Here, m is the vehicle mass, l is the wheelbase length, l_f and l_r are the respective distances from the front and rear wheels to the center of gravity position, and K_f and K_r are the respective cornering powers of the tires per unit slip angle generated at the front and rear wheels. This equation takes into account the influence of aerodynamic characteristics including the lateral force produced during steady-state cornering, so it uses the ΔK_{aero_f} of Eq. (3) and ΔK_{aero_r} of Eq. (4) as the respective equivalent cornering powers acting on the front and rear wheels (Fig. 3).

$$\Delta K_{aero_f} \cong -\frac{1}{2l} \frac{l_f K_f}{l_r K_r} \left(l_r \frac{\partial F_{aero_y}}{\partial \beta} + \frac{\partial M_{aero_z}}{\partial \beta} \right) \quad (3)$$

$$\Delta K_{aero_r} \cong -\frac{1}{2l} \left(l_r \frac{\partial F_{aero_y}}{\partial \beta} - \frac{\partial M_{aero_z}}{\partial \beta} \right) \quad (4)$$

Here, β is the slip angle when cornering, F_{aero_y} is the lateral force acting on the vehicle, and M_{aero_z} is the yawing moment around the vertical axis of the vehicle center of gravity.

Understeer characteristics result when A_{aero} is positive, and oversteer characteristics when A_{aero} is negative. Therefore, the target was set with an A_{aero} that is always greater than zero at the target speed of 450 km/h or less,

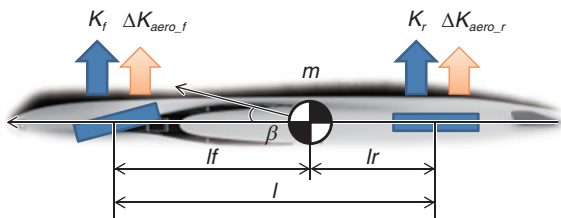


Fig. 3 Stability factor model diagram

Table 3 Aerodynamics design requirement

Category	Item	Target
Target speed		450 km/h
Aerodynamics	Specific drag	CDA < 0.09
	Body lift	CL < 0
Vehicle stability	Stability factor	$A_{aero} > 0$
	Wheel load variation at front and rear wheels	$\Delta Wtf_{-\alpha} > 0$ $\Delta Wtr_{-\alpha} > 0$

ensuring the vehicle to drive stably in a straight line even when disturbances occur.

3.4. Flipping Suppression

When vehicle attitude is disturbed by road surface input due to rutting and level differences, the vehicle nose may rise up (pitching), and air flowing to the underside of the body may generate lift on the body and further promote pitching, with the result that the flipping phenomenon occurs. This calls for some force that acts to return the vehicle to the original attitude when pitching occurs in order to secure stability.

Therefore, the target was set as front wheel load variation $\Delta Wtf_{-\alpha}$ and rear wheel load variation $\Delta Wtr_{-\alpha}$, ones that are always positive even when the pitching angle (α) changes, as shown in Eq. (5) and Eq. (6) (Fig. 4).

$$\Delta Wtf_{-\alpha} = Wtf_{-\alpha} - Lf_{-\alpha} > 0 \quad (5)$$

$$\Delta Wtr_{-\alpha} = Wtr_{-\alpha} - Lr_{-\alpha} > 0 \quad (6)$$

Here, $Wtf_{-\alpha}$ and $Wtr_{-\alpha}$ are the respective vehicle wheel loads at the front and rear wheels, and $Lf_{-\alpha}$ and $Lr_{-\alpha}$ are the respective lift forces acting on the front and rear wheels.

Table 3 summarizes the aerodynamic performance design requirements needed to achieve both the target speed and vehicle stability described in this chapter.

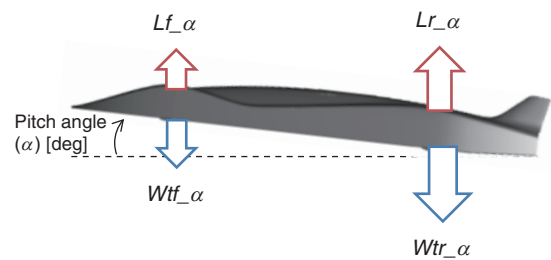


Fig. 4 Wheel load variation of car weight and lift force when pitching

4. Body Shape Design

Fluid simulation was used to investigate a body shape that achieves the target drag and lift, using a prototype model devised from initial investigations, and as references,

three models with different features selected from among the top record holder Bonneville machines. Figure 5 shows the respective body shapes and section pressure distributions obtained by fluid simulation and Fig. 6 shows the CD and CL results.

These results show that the prototype model has the smallest CD, and that reference model 2 has the smallest CL. Comparison of CL for the prototype model and reference model 2 revealed that the top position of the prototype model body shape is located toward the front of the body, so positive lift is generated at the front wheels. In addition, the greater slope angle from the nose to the top position also increases lift. Furthermore, reference model 2 results show that the incline (diffuser) from the underfloor to the rear end generates negative lift. Therefore, the contributions of the top position and height and the incline

angle were investigated to achieve a negative CL value based on the prototype model shape that has the smallest CD. Fig. 7 shows this modified model.

The modified model had a CDA of 0.085 and a negative CL value, so a body shape that achieves the target drag and lift could be designed.



Fig. 7 Shape and section pressure distribution of modified model

5. Vehicle Stability Confirmation

5.1. Stability Factor Confirmation and Countermeasures

Simulations were performed to assess whether vehicle stability could be secured while driving at high speeds. Figure 8 shows the A_{aero} calculation results for the modified model shown in Fig. 7. This shows that the A_{aero} of the modified model body shape falls below zero and results in the vehicle becoming unstable (oversteer characteristics) at velocities greater than 400 km/h.

The reason for this was investigated, and it was found that the M_{aero_z} coefficient CYM/ β (yawing moment coefficient (CYM) per unit slip angle (β)) was a large value, indicating that a moment of excessive turning force is produced on the vehicle (Fig. 9).

In addition, investigation of the lift coefficients (CLf, CLr) acting on the front and rear wheels shown in Fig. 10 revealed that the downforce on the front wheels is larger than that on the rear wheels, so the cornering force of the front wheels is stronger than that of the rear wheels and the stability factor A_{aero} drops as the velocity increases.

Therefore, measures focused on CYM/ β , CLf and CLr so that $A_{aero} > 0$, even at the target speed.

A vertical wing was attached to the rear of the body to reduce CYM/ β . In addition, horizontal wings were attached to the vertical wing and measures were taken to increase the downforce on the rear wheels, in order to reduce CLf and increase CLr while maintaining a negative CL value. Figure 11 shows the vertical and horizontal wing shapes.

In addition, the nose cone shape and the shape around the tires and other areas were modified to enhance the balance between CD, CLf and CLr, and the body shape of the race car was decided. Figure 12 shows the body shape and section pressure distribution of the race car model.

Figure 8 shows the A_{aero} , Fig. 9 shows the CYM/ β , and Fig. 10 shows the CLf and CLr of the race car model. The results in Fig. 8 confirmed that the race car model has an A_{aero} greater than zero even at velocities of 450 km/h or more.

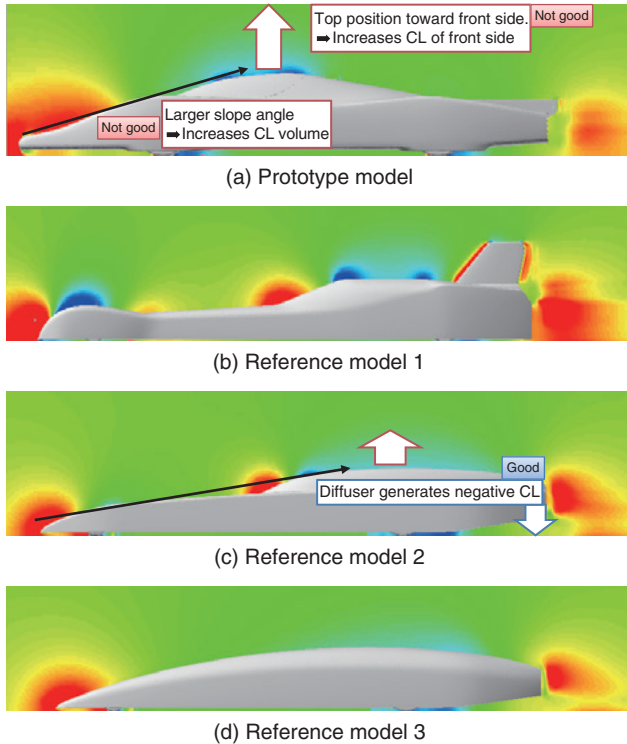


Fig. 5 Comparison of section pressure distribution of 4 models

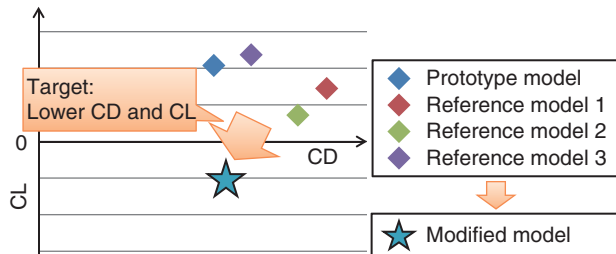


Fig. 6 CD and CL of 5 models

5.2. Confirmation of Flipping Suppression

The wheel load variation was confirmed over a pitching angle range from 0 deg to 5 deg with the rear wheels as the fulcrum for when vehicle pitching occurs at the target speed of 450 km/h.

Figure 13 shows the calculation results for the race car model. Both the front wheel load variation $\Delta W_{tf_}\alpha$ and rear wheel load variation $\Delta W_{tr_}\alpha$ are constantly positive values at each pitching angle, which confirmed that this body

shape suppresses flipping.

The vertical and horizontal wings are drag factors, but were added to the race car model to enhance the CYM, CLf and CLr characteristics compared to the modified model. The resulting CDA was 0.089, which met the target, so the race car cowl was manufactured based on the body shape of the race car model shown in Fig. 12.

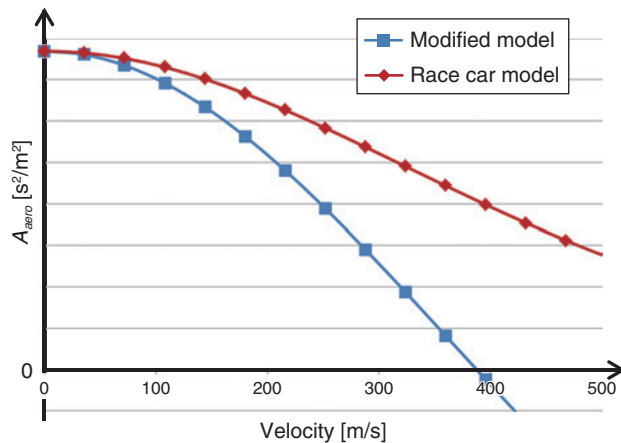


Fig. 8 Comparison of stability factor of modified model and race car model

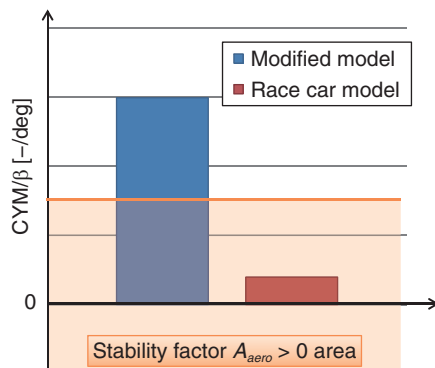


Fig. 9 Comparison of CYM/β of modified model and race car model

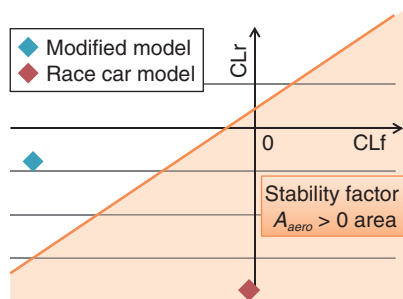


Fig. 10 Comparison of CLf and CLr of modified model and race car model

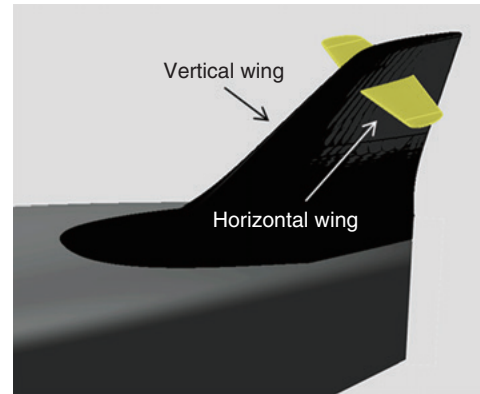


Fig. 11 Attached vertical and horizontal wing



Fig. 12 Shape and section pressure distribution of race car model

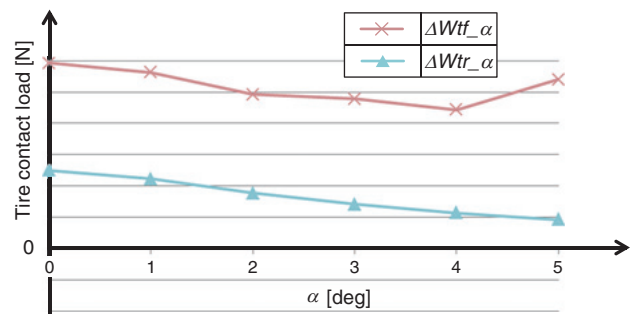


Fig. 13 Relationship between pitching angle and wheel load variation of race car model at 450 km/h

6. Body Shape Design Change

Test runs were conducted by the driver on a test course in Japan before transporting the race car to the Bonneville race site, and confirmed that there were no issues with vehicle stability, maneuverability, visibility or other factors that might hinder driving.

The team then participated in Mike Cook's Bonneville

Test & Tune, held during the two weeks prior to Speed Week, and conducted test runs on the race course. The Bonneville Salt Flats are an environmental conservation district, so lines were not drawn for the Speed Week race course and the only landmarks were traffic pylons placed at 1/4-mile intervals on the white, salt course surface. Furthermore, the vibration felt when driving reduced pylon visibility and revealed that course deviation was an issue. To address this issue, the body shape design was changed to provide the driver sufficient visibility to recognize the pylons as well as secure the vehicle aerodynamic performance and stability needed to achieve the target speed.

Figure 14 is the revised body shape and the fluid simulation results of the section pressure distribution. Figure 15 presents the CD and CL calculation results, Fig. 16 displays the CLf and CLr, Fig. 17 shows the change in A_{aero} due to vehicle velocity, and Fig. 18 shows the wheel load variation.

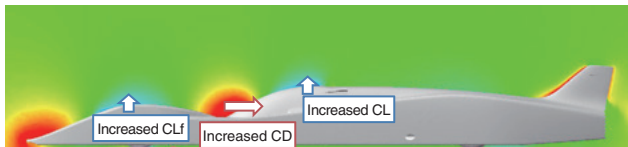


Fig. 14 Shape and section pressure distribution of race car revision model

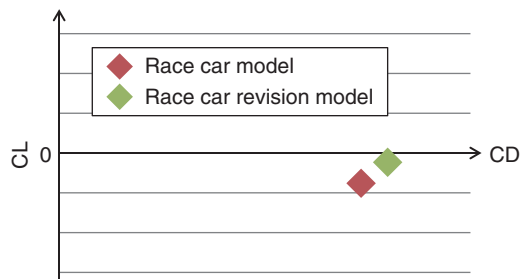


Fig. 15 Comparison of CD and CL of race car model and race car revision model

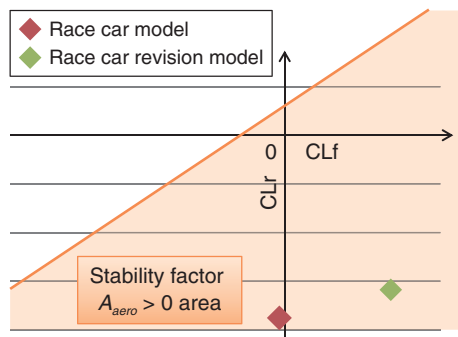


Fig. 16 Comparison of CLf and CLr of race car model and race car revision model

The shape change was confirmed to increase CD and bring CL close to zero, as shown in Fig. 15.

The reasons were because the newly attached windshield had a larger angle of inclination, which increased the drag, and cutting down the area around the front wheels to secure forward visibility increased the lift.

In addition, since the lift around the front wheels increased, CLf became a positive value as shown in Fig. 16. However, this was confirmed to make A_{aero} more stable at higher velocities, as shown in Fig. 17.

The shape change also altered the pitching angle, which increased the wheel load variation as shown in Fig. 18, but it was confirmed that the target requirement was met.

The race car revision model provided sufficient visibility and met vehicle stability requirements, but the CDA was 0.097, which did not achieve the target.

A check process using fluid simulation had been developed, so that shape design changes could be made, and vehicle stability was checked in a short period of just three days.

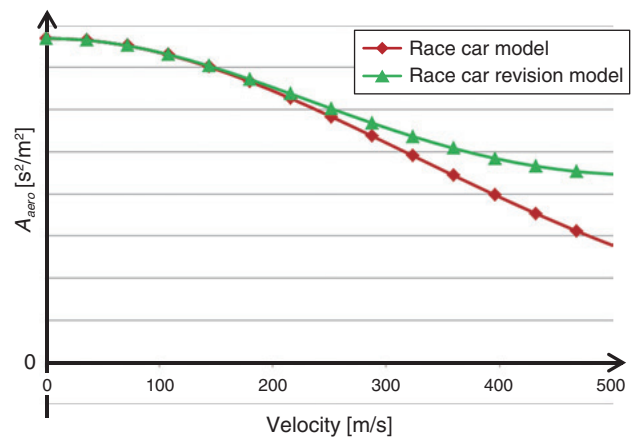


Fig. 17 Comparison of stability factor of race car model and race car revision model

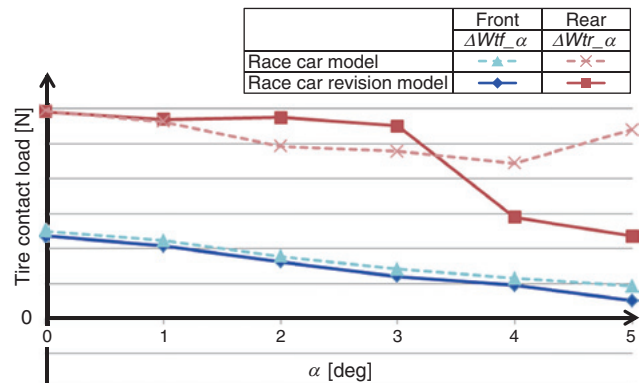


Fig. 18 Relationship between pitching angle and wheel load variation of race car model and race car revision model at 450 km/h

Table 4 Mike Cook's Bonneville Shootout (FIA recognized) participation category

Category A	Race car
Group 1	Otto cycle engine with supercharger
Class 4	Engine displacement 500-750 cm ³
Start	Flying start

Table 5 FIA Land Speed Record result

Vehicle	Honda S-Dream Streamliner
Constructor	Team Honda R&D
Driver	Hikaru Miyagi
1 mile record	261.875 mile/h (421.446 km/h)
1 km record	261.966 mile/h (421.595 km/h)

7. Race Participation Results

A new record in the target participation category was not achieved during Bonneville Speed Week, however, the team was invited to Mike Cook's Bonneville Shootout (FIA World Land Speed Records) held in September, and participated in the Category A, Group 1, Class 4 race. Table 4 shows the participation category⁽⁴⁾.

As a result, a speed of 421 km/h was achieved⁽⁵⁾, which is the top speed record in the participation category (Table 5).

8. Conclusion

The following aerodynamics development was performed for a Bonneville race car to achieve a set target speed of 450 km/h.

- (1) Aerodynamic performance was compared and investigated with the goal of achieving the targeted speed, and these results were used to design a body shape with a body drag coefficient * frontal projected area (CDA) and a lift coefficient (CL) that were at the targeted values, or less.
- (2) Vertical and horizontal wings were attached to the vehicle, which enabled to suppress spin and flipping while securing high-speed driving stability.
- (3) A developed process allowed the body shape design changes needed to secure visibility while taking into account aerodynamics and to confirm the vehicle stability in a short time.
- (4) The target speed was not achieved during Bonneville Speed Week, but the team was invited to Mike Cook's Bonneville Shootout held afterwards, setting an official FIA World Speed Record of 421 km/h in the participation class.

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