

Differences between Air-Dam Spoiler Performances in Wind Tunnel and On-Road Tests

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ABSTRACT

An air-dam spoiler is commonly used to reduce aerodynamic drag in production vehicles. However, it inexplicably tends to show different performances between wind tunnel and coast-down tests. Neither the reason nor the mechanism has been clarified.

We previously reported that an air-dam spoiler contributed to a change in the wake structure behind a vehicle. In this study, to clarify the mechanism, we investigated the coefficient of aerodynamic drag C_D reduction effect, wake structure, and underflow under different boundary layer conditions by conducting wind tunnel tests with a rolling road system and constant speed on-road tests.

We found that the air-dam spoiler changed the wake structure by deceleration of the underflow under stationary floor conditions. Accordingly, the base pressure was recovered by approximately 30% and, the C_D value reduction effect was approximately 10%. The ratio of the base pressure recovery to the C_D value reduction effect was approximately 90%, suggesting that the main mechanism is the base pressure recovery produced by changing the wake structure. In contrast, the air-dam spoiler did not change the wake structure in on-road tests and under moving floor conditions. Consequently, the base pressure recovery and C_D value reduction effect decreased to approximately 20% and 4%, respectively, owing to the deceleration of the underflow being insufficient to change the wake structure. In other words, the boundary layer of the floor helped to decelerate the underflow and to change the wake structure under stationary floor conditions, suggesting that we overestimated the air-dam spoiler performance under stationary floor conditions.

CITATION: Katoh, D., Koremoto, K., Kaneko, M., and Hashizume, Y., "Differences between Air-Dam Spoiler Performances in Wind Tunnel and On-Road Tests," *SAE Int. J. Passeng. Cars - Mech. Syst.* 7(2):2014, doi:10.4271/2014-01-0609.

INTRODUCTION

Modern vehicles have some aerodynamic components or aerodynamic shapes. These enhancements are developed by computational fluid dynamics (CFD) and wind tunnel tests during vehicle design and then evaluated during on-road tests. However, the aerodynamic components may show different performance in wind tunnels and on-road tests. Studies are investigating the influence of the boundary layer, natural wind, tire rotation, etc. to solve this problem. Unfortunately, few studies have focused on the mechanism of actual aerodynamic components of production vehicles in on-road tests. The present study focuses on an air-dam spoiler and studies the C_D value reduction effect and its mechanism.

A previous paper compared the C_D value reduction effect of an air-dam spoiler between wind tunnel and coast-down tests [1]. The wind tunnel tests were conducted at the Suzuki wind tunnel under stationary floor conditions. We clarified that the air-dam spoiler reduced the C_D value through base pressure recovery caused by the change in the wake structure behind the vehicle (see [Appendix D](#)). However, the C_D value reduction effect was the same whereas the base pressure recovery differed by approximately 16% between the wind tunnel and the coast-down tests. The cause was not clarified because there were some differences such as deceleration flow, boundary layer condition, and tire rotation between the wind tunnel and the coast-down tests.

In this study, we conducted the constant vehicle speed on-road tests and wind tunnel tests using a rolling road system to bridge the difference between the wind tunnel and the coast-down tests. In the on-road tests, the C_D value was measured using two torque sensors on the drive shafts. Furthermore, the influence of the natural wind was ignored during the on-road test results because the weather was calm. Under these conditions, we studied the differences between the air-dam spoiler performance in wind tunnel and on-road tests.

EXPERIMENTAL SECTION

All details related to each topic can be found in the Appendices.

Test Vehicle

The test vehicle of this study was the Suzuki Cervo (Figure 1), a five-door hatchback in the category of small Japanese vehicles known as Kei vehicles. The major specifications of this vehicle are listed in Table 1. A 45 mm high and 800 mm wide air-dam spoiler was specifically designed for this study and attached to the lower end of the front bumper. We studied its effect on the aerodynamic drag C_D through wind tunnel and on-road tests.

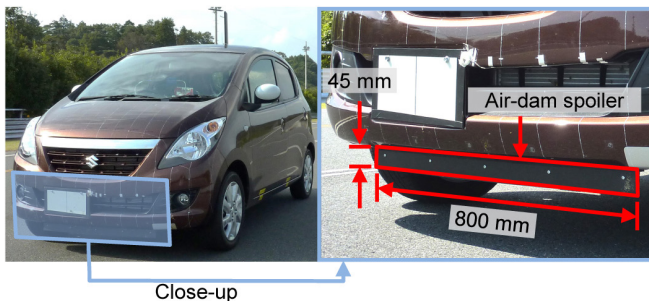


Figure 1. Photograph of test vehicle and air-dam spoiler

Table 1. Major specifications of test vehicle

Body shape	5-door hatchback
Overall dimensions L × W × H [mm]	3,395 × 1,475 × 1,535
Engine	0.66 L DOHC 12-valve 3-cylinder
Tires	165/55R14
Wheelbase [mm]	2,360
Total weight [kg]	Approximately 1017
Frontal area [m ²]	1.954

Wind Tunnel

The wind tunnel tests were conducted in the full-scale automotive wind tunnels of Suzuki Motor Corporation and Honda R&D Co., Ltd., under different boundary layer conditions. The specifications of both wind tunnels differ

slightly, as described below. However, these differences do not have any significant impact on the flow phenomena around the vehicle, as noted in Appendix C.

Suzuki Wind Tunnel

The Suzuki wind tunnel is a 3/4 open-jet type. The nozzle exit area is 16.0 m² (5.5 m × 3.1 m) [1]. The blockage ratio of the test vehicle was 0.12. The wind tunnel has a conventional 6-component balance. Therefore, the floor is stationary. The boundary layer thickness is approximately 45 mm at the center of the turn table. Moreover, the axial static pressure gradient on the turntable is -0.01. The C_D values were therefore corrected using Mercker's blockage correction method [2].

Honda Wind Tunnel

The Honda wind tunnel is also a 3/4 open-jet type. The nozzle exit area is 24.1 m² (6.7 m × 3.6 m) [3]. The blockage ratio of the test vehicle was 0.08. This wind tunnel has a rolling road system (RRS) with a large single belt for simulating precise real-world flow phenomena. The RRS is used for precise C_D measurement by a horizontal force measuring (HFM) system, because the measured data does not include tire rolling resistance and drive friction [3]. The boundary layer thickness is approximately 80 mm at the center of the turn table under RRS-off conditions. The boundary layer was negligible under RRS-on conditions. Moreover, the axial static pressure gradient on the turntable is negligible under both RRS-off/on conditions [3].

Test Circuit

The on-road test was conducted on the Japan Automobile Research Institute's high-speed testing circuit, which has a circumferential length of 5,500 m. All tests were conducted in the two straight sections of the circuit, each of which is approximately 1,100 m in length, as shown in Figure 2.

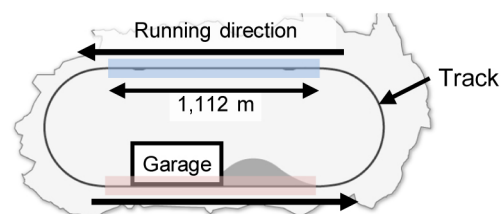


Figure 2. Schematic illustration of Japan Automobile Research Institute's high-speed testing circuit

On-Vehicle Measurement System

The equipment for measuring the C_D value, base pressure, and total pressure of the underbody flow were mounted on the test vehicle in both the wind tunnel and the on-road tests. A block diagram of the measurement system is shown in Figure 3.

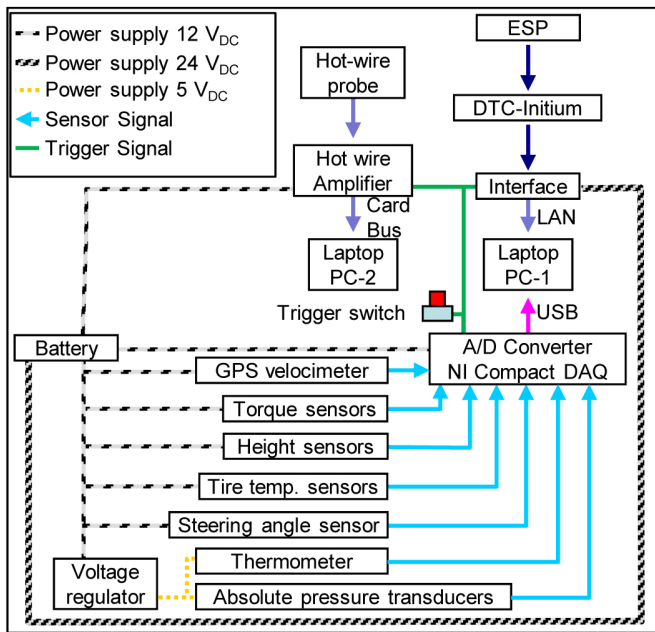


Figure 3. Schematic illustration of on-vehicle measurement system

GPS Velocimeter

A GPS velocimeter (VBOX3i+IMU, Racelogic Ltd.; accuracy, 0.1 km/h; resolution, 0.01 km/h) was used to measure the vehicle speed V_{GPS} . The outputs of the GPS velocimeter were recorded in synchrony with the signals from the other equipment.

Hot-Wire Anemometer

A hot-wire anemometer (IHW-100, KANOMAX JAPAN Inc.) and an X-shaped probe (1241-10, TSI Inc.) attached by a holder on the roof of the test vehicle were used to measure the wind velocity V_W and direction. The probe tip was located 300 mm above the center of the roof curvature, as shown in Figure 4. Further, the probe direction was adjusted to the positioning mechanism by 0° in the wind tunnel test (see Appendix A-1). The velocity measured by the hot-wire anemometer was higher than the wind velocity V_W because the roof curvature accelerated the surrounding air flow. The wind velocity was therefore calculated using the calibration formula (Eq. 1) from the output of the hot-wire anemometer in the on-road tests. The calibration formula was derived from the relationship between the mean velocity of the wind tunnel, V_W , and the velocity of the hot-wire anemometer, V_{HW} (see Figure 5).

Figure 6 shows examples of the C_D value in the on-road tests. The plot distributions on the left- and the right-hand side respectively show the C_D values calculated using the GPS vehicle speed V_{GPS} and the wind velocity V_{CW} through the hotwire anemometer. The C_D values calculated using V_{GPS} (on the left) showed no clear pattern when the standard deviation (SD) was 0.011; on the other hand, those calculated using V_{CW} (on the right) were consistent when the SD was 0.006. This suggests that using V_{CW} is valid for calculating the C_D value in the on-road tests.

$$V_W \cong V_{CW} = 0.908 V_{HW} + 0.838 \quad (1)$$

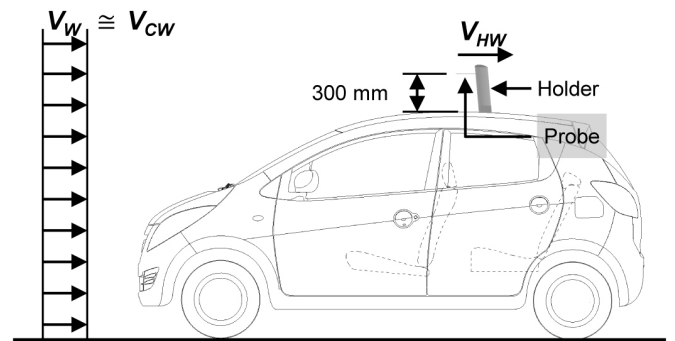


Figure 4. Schematic illustration of roof mounted hot-wire anemometer

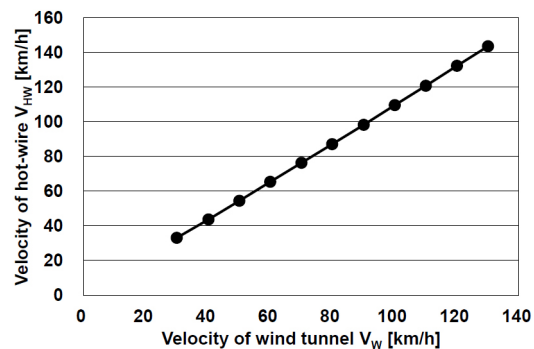
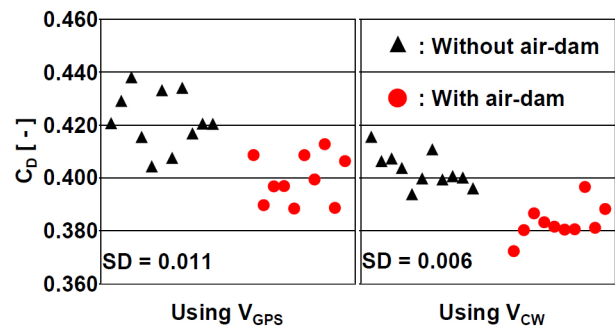


Figure 5. Relationship between mean velocity of wind tunnel and velocity of hot-wire

Figure 6. Comparison of C_D value calculated using GPS vehicle speed V_{GPS} and wind velocity V_{CW} by hot-wire anemometer.

Torque Sensor on Drive Shaft

Two torque sensors were mounted on each drive shaft to measure the C_D value under constant vehicle speed condition in the on-road tests. Generally, the C_D value is measured by the coast-down method in on-road tests. However, the results of coast-down tests cannot be compared directly with those of wind tunnel tests because the wind velocity condition is different. The wind velocity decelerates in coast-down tests, whereas it is constant in wind tunnel tests. In this study, the on-road tests were conducted under constant vehicle speed conditions to homologize the wind velocity condition between the wind tunnel tests and the on-road tests.

We focused on the balance between the driving force F_{Drive} and the running resistance R_{Run} based on Newton's first and second laws under constant vehicle speed conditions. The running resistance was resolved into the aerodynamic drag R_{Aero} , mechanical losses R_{Mech} , acceleration resistance, and hill climbing resistance [4]. In this study, the hill climbing resistance was negligible because the gradient of the test course was approximately zero. The acceleration resistance was also negligible because of the constant vehicle speed. Therefore, the driving force is as expressed by Eq. 2. Consequently, the aerodynamic drag can be calculated by subtracting the measured mechanical losses from the measured driving force, as expressed by Eq. 3.

$$[F_{Drive}]_{on-road} = [R_{Run}]_{on-road} = [R_{Aero} + R_{Mech}]_{on-road} \quad (2)$$

$$[R_{Aero}]_{on-road} = [F_{Drive} - R_{Mech}]_{on-road} \quad (3)$$

The driving force was measured by the torque sensors (ILW21D, Takasu Technical Laboratory) mounted on each drive shaft (see Figure 7). The sensors did not affect the aerodynamic characteristics of the vehicle because they were small in size. Figure 8 shows a schematic illustration of the sensors.

Mayer and Wiedemann (2003) proposed that mechanical losses could be subdivided into rolling resistance R_{Roll} , drive train losses R_{DT} , wheel bearing and brake friction R_{BB} , tire slip losses R_{Slip} , wheel ventilation losses R_{WV} , and wheel suspension parasitic losses R_{PW} , as expressed by Eq. 4 [4].

$$R_{Mech} = R_{Roll} + R_{DT} + R_{BB} + R_{Slip} + R_{WV} + R_{PW} \quad (4)$$

Slip losses were assumed to be zero because the on-road tests were conducted under straight running and constant vehicle speed.

In this study, the mechanical losses were measured through chassis dynamometer tests (see Figure 9). The results were corrected for the tire contact patch [5]. The drive train losses R_{DT} were synchronously measured using the torque sensors on the drive shafts.

$$[R_{Roll}]_{Chassis} = [R_{Mech} - (R_{DT} + R_{BB} + R_{WV} + R_{PW})]_{Chassis} \quad (5)$$

The output of the torque sensors during the on-road tests is given by Eq. 6, which is derived from Eqs. 2 and 4.

$$[F_{Drive}]_{on-road} = [R_{Aero} + R_{Roll} + R_{DT} + R_{BB} + R_{WV} + \dots + R_{PW}]_{on-road} \quad (6)$$

The R_{BB} , R_{WV} , and R_{PW} values obtained by the chassis dynamometer test and the on-road tests were assumed to be similar. Hence, the parameters were canceled out from Eq. 7, which is obtained by substituting Eq. 2 into Eq. 6.

$$[F_{Drive}]_{on-road} = [R_{Aero}]_{on-road} + [R_{Mech} - R_{DT}]_{Chassis} \quad (7)$$

The aerodynamic drag was calculated using Eq. 8.

$$[R_{Aero}]_{on-road} = [F_{Drive}]_{on-road} - [R_{Mech} - R_{DT}]_{Chassis} \quad (8)$$

In the actual data processing, the raw data of the torque sensor output had an amplitude of about 30 N, as shown in Figure 10. This was due to the intermittent combustion of the reciprocating engine, as shown in Figure 11. The torque fluctuation was filtered from the outputs by a digital low-pass filter having an acausal zero phase-shifting finite impulse response, as shown in Figure 10 [6]. We treated the filtered data to calculate the C_D value.

In this study, the C_D value reduction effects of the air-dam spoiler were calculated by subtracting without air-dam spoiler measurements from with air-dam spoiler measurements. The results were therefore unaffected by the assumed resistances R_{Slip} , R_{BB} , R_{WV} , and R_{PW} in each test.

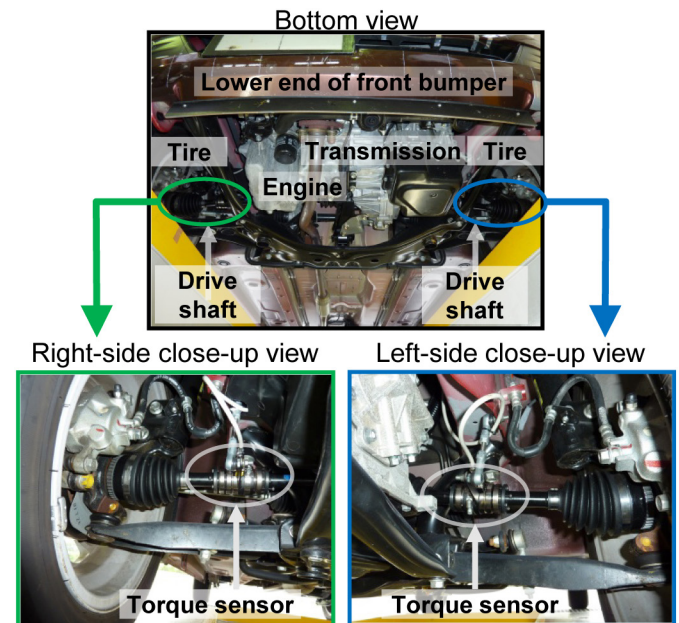


Figure 7. Photograph of mounted torque sensors on drive shafts

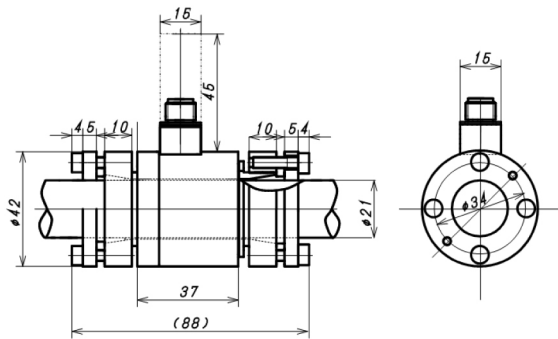


Figure 8. Schematic illustration of torque sensor



Figure 9. Photograph of chassis dynamometer test

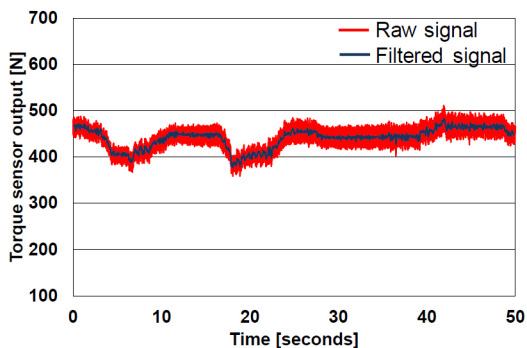


Figure 10. Comparison of powertrain output signals

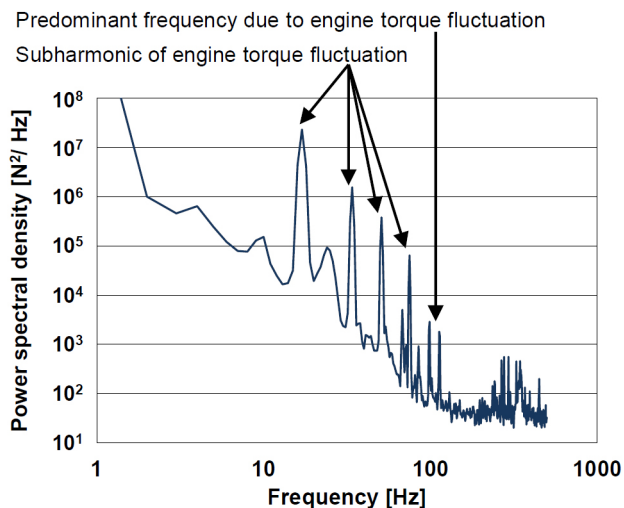
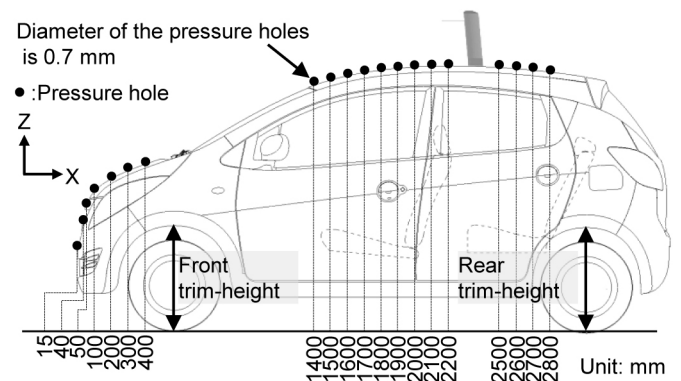


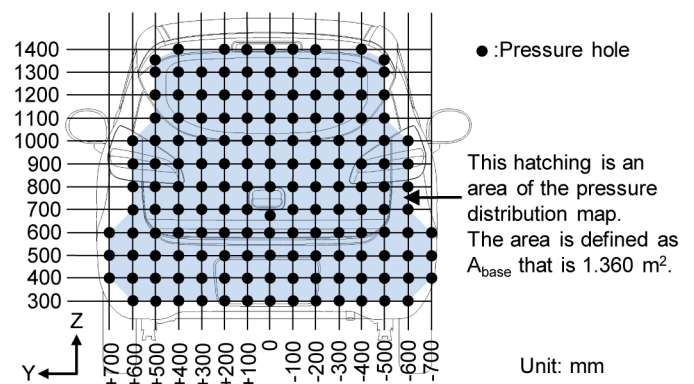
Figure 11. Power spectral density of power train output signal

Pressure Sensor

We measured the pressures on the surface of the test vehicle and the total pressure under the rear bumper to compare the wake structures in the wind tunnel and the on-road tests. These pressures exerted through the plastic tubes from the pressure holes were measured using multiple pressure transducers, which were a combination of a DTC-Initium, three ESP-64s, and two ESP-32s made by Pressure System, Inc. The locations of the pressure holes are shown in Figure 12. The multiple pressure transducers recorded 256 differential pressures between the reference pressure and the pressures of the measuring points. The reference pressure was supplied from the thermostatic air chamber in the on-road tests [1]. The magnitude and phase of the measured pressures were corrected using the tubing transfer function [1, 7, 8]. The surface pressure measured on the back surface, also known as the base pressure, was mapped to the 3D CAD data of the test vehicle using the data analyzing software, FieldView®. Further, this mapped data was analyzed as an X-component of the areal mean C_p value.

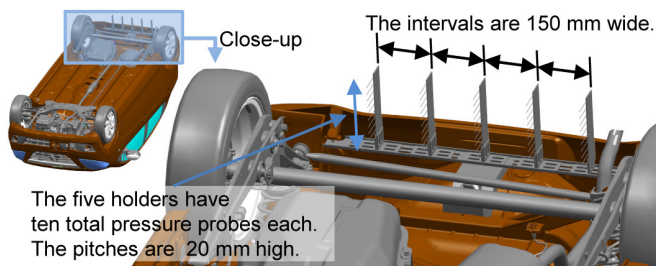


a). Side view



b). Rear view

Figure 12. Schematic illustration of pressure measuring points



c). Total pressure probe rake under rear bumper

Figure 12. (cont.) Schematic illustration of pressure measuring points

Height Sensor

Four laser height sensors were used to measure the vehicle height because the heights in the wind tunnel tests needed to be matched with those in the on-road tests. The measurement was performed using four ILD1401-250V sensors (MicroEpsilon) mounted on the floor of the test vehicle. The sensors irradiated the road surface by laser beams through the floor holes to measure the height (see [Appendix A-2](#)).

Tire Temperature Sensor

The rolling resistances depend on the tire temperatures and vehicle speed [9]. Four tire temperature sensors (INFB1-200, Texsys International) were installed on each fender lining to monitor the tire conditions and extract the stable tire condition from the sampling data (see [Appendix A-3](#)).

Steering Angle Sensor

The steering angle sensor (X21, MoTeC Pty. Ltd.) was used to monitor the steering angle in the on-road tests. If the steering angle is not zero, the actual rolling resistance would be higher than the rolling resistance measured in the chassis dynamometer tests, which were conducted under straight driving conditions (see [Appendix A-4](#)).

Measuring Condition

The wind tunnel and on-road tests were conducted at a constant speed of 100 km/h in a straight line. The major specifications of the data acquisition are listed in [Table 2](#). The extraction conditions used to calculate the stable C_D value in the on-road tests are also listed in [Table 3](#).

Table 2. Major specifications of data acquisition

	A/D converter	Multiple pressure transducer	Hot-wire anemometer
Sampling rate	1,000 Hz	250 Hz	1,000 Hz
Sampling number	50,000	12,500	50,000
Resolution	16 bit	18 bit	16 bit
Input range	-5 to +5 V	-2 to +2 kPa	0 – 180 km/h

Table 3. Extraction conditions of on-road tests

Vehicle speed (V_{GPS})	100 ± 1 km/h
Wind velocity (V_W)	$V_{GPS} \pm 3$ km/h
Yaw angle (α_Y)	$\pm 2^\circ$
Acceleration (a_Y)	± 0.001 G (minimum resolution)
Steering angle (α_{ST})	$0 \pm 0.5^\circ$
Tire temperature (T_T)	$\pm 1.5^\circ\text{C}$

Results

Air-Dam Performance and Mechanism under Stationary Floor Conditions in Suzuki Wind Tunnel

As mentioned in the introduction, the air-dam spoiler reduces the C_D value via base pressure recovery behind the vehicle. In this study, the total pressures of the underflow were measured using the total pressure probe rake to determine the mechanism by which the base pressure is recovered.

The underflow was decelerated by attaching the air-dam spoiler, as shown in [Figure 13](#) (see [appendix B-1](#) for methodology). The areal mean C_p of Section-1 was located 20mm behind the attachment point of the air-dam spoiler. The areal mean C_p was reduced from 1.00 to 0.68. Hence, the inlet flow under the front bumper was reduced by approximately 30%. In addition, the inlet ratio ΔC_{p_Total} decreased from section one (–32%) to section four (–85%). It is assumed that the underflow blows out of the side between sections one and four. As a result, the two wake structures near the front tire are influenced as shown in [Figure 14](#) (see [appendix B-2](#) for methodology) [1]. [Figure 15](#) shows the base pressure and total pressure under the rear bumper. The C_D value reduction effect was 7.8%. Further, the X-component of the areal mean base pressure C_{p_base-X} was recovered by 26.5%, which is equivalent to 94% of the C_D value reduction effect. The ratio of C_{p_base-X} recovery to C_D value reduction effect is approximately 100%. Therefore, the main mechanism of the air-dam spoiler's effect is to recover the base pressure. In particular, the highest-pressure region moved up from $Z = 400$ mm to $Z = 700$ mm after attaching the air-dam spoiler. As explained later, the highest-pressure region was caused by the vortex generated by the underflow striking the back surface of the vehicle. Consequently, the region of C_{p_base} recovery was anywhere above $Z = 600$ mm, as shown in [Figure 15\(b\)](#). Furthermore, the underflow was slowed down by attaching the air-dam spoiler.

To determine the relationship between the changing wake structure and the slowdown of the underflow, the total pressure distributions behind the vehicle were measured at two cross sections as shown in [Figure 16](#) (see [appendix B-2](#) for methodology). The upper distribution maps (a) show the measured cross section 300 mm behind the vehicle. The lower maps (b) show the central sections behind the vehicle. The deceleration of the underflow by the air-dam spoiler was similar to that shown in [Figure 15](#). Therefore, the pressure recovery