Aerodynamic drag reduction of a simplified vehicle model by promoting flow separation using plasma actuator

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Abstract
In recent years, the dielectric barrier discharge plasma actuator (DBD-PA), which is a fluid control device, has been investigated for achieving both high aerodynamic performance and pleasing styling of transportation equipment. In this study, the authors installed a DBD-PA system on a simplified three-dimensional bluff automobile body to reduce the aerodynamic drag. In particular, the authors focused on the sides of the rear end of the body, where the local shape has high sensitivity regarding both styling and aerodynamic drag. At the rear sides of the automobile-like bluff body, a sharp edge rather than a smooth rounded corner often reduces the aerodynamic drag by promoting airflow separation. Therefore, the authors aimed to reduce the aerodynamic drag by using a DBD-PA system to promote flow separation at the rear end while retaining its rounded shape. Aerodynamic measurements using a one-fifth scale simplified automobile model were conducted in a wind tunnel. Preliminary investigation of the aerodynamic effect at the rear clarified how the longitudinal vortices from the rear pillar and the side edge of the trunk deck cause the drag increase at the rear-end corners. Two parallel DBD-PAs were installed on the rear surface to shift these vortices away from the corners by promoting flow separation. The drag reduction rate reached 3% at the highest applied voltage using the DBD-PA system on a rounded shape, and it achieved approximately half the effect of the sharp-edged shape. The longitudinal vortices were successfully kept away from the rear-end corners by the DBD-PAs. The surface pressure increased with the displacement of the vortices, which led to the drag reduction observed.

Keywords: Drag reduction, External flow, Separation, Flow control, Automobile, Aerodynamics, Plasma actuator, Experimental fluid dynamics (EFD)

1. Introduction
Improvement of aerodynamic performance has become an increasingly important issue in automobile development, as regulations on emissions from automobiles have become stricter owing to the growing concern with global warming issues. In conventional aerodynamic analysis and development of automobiles, the aerodynamic drag coefficient \( C_D \) has been reduced by investigating the dependence of \( C_D \) on the local geometry of the vehicle body (Kobayashi and Nouzawa, 1998) and by modifying the shape of the vehicle body. However, the shape modification for aerodynamic
drag reduction constrains the styling of an automobile, which strongly affects its merchantability. Therefore, to solve this conflict between aerodynamic drag reduction and styling freedom, a new flow control technique that does not require modifying the shape of the vehicle body is required. As one such flow control technique, the dielectric barrier discharge plasma actuator (DBD-PA; hereinafter simply referred to as PA) is of interest. PA has less influence on styling owing to its very thin structure with no moving parts.

The PA consists of two electrodes sandwiching a dielectric; it generates an induced fluid flow by applying an alternating high voltage between the electrodes (Corke et al., 2010). With regard to control of the fundamental flow, such as control of the cylinder wake (Jukes and Choi, 2009) and the backward-facing step flow (Sujar-Garrido et al., 2015; Otsuka et al., 2016), the PA has been demonstrated to successfully reduce the wake flow by inducing a flow affecting the separated shear air layer. Furthermore, the PA is beginning to be widely applied in uses other than the suppression of flow separation. In the backward-facing step flow, the burst mode, in which the PA operates intermittently at a certain frequency, promotes the collapse of the periodically shed vortex present in the separated shear layer, and it increases the distance of the reattachment point from the step (Kikuchi et al., 2018).

With regard to transportation equipment, PA has also been applied to flow around wings, railway pantographs (Mitsumoji et al., 2012), automobile bodies, and others. In particular, many studies focusing on improvement of wing performance by suppressing the flow separation (Sato et al., 2015; Fujii, 2018) have been conducted in the aerospace field. Regarding applications of PA on automobile flow, aerodynamic noise reduction (Miyamoto et al., 2018) and aerodynamic drag reduction (Shadmani et al., 2018; Kanatani et al., 2009; Vernet et al., 2018) have been studied. These studies aimed to reduce the boundary layer separation from the automobile’s body, such as at the roof’s end or the rounded pillar, similar to suppressing flow separation on a wing. Vernet et al. (2018) mounted a PA in a U-shape configuration to induce a longitudinal vortex to suppress the flow separation at the rounded pillar surface. Conversely, the aerodynamic drag of an automobile can also be reduced by promoting flow separation on the body surface. Considering the comfort and capacity of the cabin, it is difficult to narrow the rear part of an automobile body sufficiently to achieve a truly streamlined shape. In such a three-dimensional bluff body, the flow acting on the corners at the rear end of the body generates an additional drag due to the Coanda effect. Therefore, using an edge shape at the rear end of the body, which promotes flow separation at the rear-end corners, is sometimes effective to reduce aerodynamic drag (Ohira et al., 2008). However, to balance styling freedom and aerodynamic performance, it is desirable to develop other techniques to promote flow separation without using the edge shape. Such techniques will allow choosing an arbitrary curved shape at the rear end without increasing the aerodynamic drag, hence increasing the degree of freedom in body styling.

Therefore, in the present study, we attempted to reduce the aerodynamic drag of an automobile with a rounded shape at the rear-end corners of the body sides by controlling flow using a PA system. Before applying the PA, we conducted wind tunnel measurements of three simplified automobile models with different curvatures at the rear end of the body side surface. Based on the drag reduction rate measured at the sharp-edged model’s rear-end corner, we determined the desired drag reduction rate using a rounded body. Comparing the flows around the models, we clarified the aerodynamic effect of the rear end shape and determined a PA set-up to promote flow separation at the rounded corners effectively. Then, we applied the PA system for active flow control and measured the aerodynamic drag change, surface pressure on the rear part of the model, and wake flow structure behind the model. From these measurement results, aerodynamic drag reduction due to the promotion of flow separation using the PA system was evaluated and its physical mechanism is discussed.

2. Experimental method
2.1 Wind tunnel facility

In this study, we measured the aerodynamic force acting on each model and observed the flow field around the model in a Göttingen-type wind tunnel at Hiroshima University. Figure 1 shows an overview of the wind tunnel facility and the coordinate axes. The wind tunnel has a square 2.0 m nozzle, the length of the measurement section from the nozzle to the collector is 4.0 m. The maximum wind speed is 25 m/s, and the turbulence intensity is less than 1% at a wind speed of 15 m/s. A ground plate was installed to suppress the boundary layer thickness on the floor under the model, and the thickness measured in the empty test section (where the model would be located) was approximately 10 mm at the streamwise location of the leading edge of the model if it were present. To avoid any airflow reduction caused by the ground plate under the model from affecting the boundary layer, we increased the height under the model.
by 10 mm compared to the original configuration of the simplified automobile model (Ichimiya and Akiyama, 2007). The origins of the X-, Y-, and Z-coordinate axes were defined at the wheel base center of the model, the center of the model width, and the bottom center of the model, respectively.

Fig. 1 Outline of the wind tunnel facility. Left and right figures show top and side views, respectively. Each model was placed facing the nozzle on a ground plate installed in the measurement section.

2.2 Investigated model

Figure 2 shows the investigated automobile models in this study. The basic model (Ichimiya and Akiyama, 2007) has a simplified geometry designed to reproduce flow structures above the trunk deck of a sedan-type production automobile. A one-fifth scale model of a real vehicle is used, whose length $L$, width $B$, and height $H$ are 840 mm, 320 mm, and 300 mm, respectively. The height of the trunk part $h$ is 160 mm and the frontal area of the model is $8.44 \times 10^{-2}$ m$^2$. To clarify the effect of PA actuation on the wake of the model, we decided to eliminate the effect of the flow generated by the wheels. Therefore, we installed four struts (NACA0024 wing sections with 50 mm chord length) to support the model at the same positions as the front and rear wheels of the original automobile. As shown in Fig.2, the height of each wing part is 32 mm in addition to a cylindrical column with 12 mm radius, which elevates the vehicle body so that it rests 10 mm above the ground plate. Each strut was connected to the balance installed under the ground plate through circular holes in the ground plate. The curvature radius of the rear end of the body side surface is $R = 40$ mm, and is the characteristic of interest in this study. Moreover, to clarify the aerodynamic effect of the shape of the rear-end corners for this model, two additional models, one with a smaller curvature radius $R = 20$ mm and one with a sharp edge ($R = 0$ mm) were also investigated. In this paper, these additional models are referred to as the “R20 model” and “edge model”, respectively, and the original is the “base model”. Moreover, the rear-end part of the body side surface is simply called the “rear-end corner”.

Fig. 2 Outline of the investigated automobile model and three variations. The body is at one-fifth the scale of a real automobile, reproducing the flow structures above the trunk deck of a sedan-type production automobile. Four struts with the cross section of the NACA0024 wing are attached instead of the four tires.
2.3 Flow control device

Figure 3 shows the configuration of the PA used for flow control in this study. Copper foil tape (3M, Cu-35C: 70 μm thickness) and polyimide film (Teraoka Seisakusyo, 650S: 80 μm thickness with 50 μm-thick base material) were adopted as the electrodes and dielectric layer, respectively. The widths of the top and bottom electrodes were both 6 mm and these electrodes overlapped by 1 mm (Fig. 3(b)). Total thickness of the PA was 0.3 mm and it was directly mounted on the model’s surface. A high-voltage AC power supply was connected to the top electrode side. The AC supply amplified a sinusoidal wave, generated by a function generator (NF Corp., WF1974), by 1,000 times and supplied it to the electrode. The waveform of the actual supplied voltage between the electrodes was measured by an oscilloscope (Yokogawa Test & Measurement Corp., DLM2054) connected using high voltage probes (Tectronix, P6015A). The applied frequency \( f_{\text{applied}} \) of the voltage applied to the PA was set to 8.0 kHz. As a basic performance indicator of this PA, we measured the flow velocity induced by a single PA unit mounted on a flat plate using Particle Image Velocimetry (PIV), where the peak-to-peak value of the applied voltage \( V_{\text{pp}} \), was varied from 3 kV to 10 kV in 1 kV increments. Figure 4 shows the maximum flow velocity on the central cut-plane of the PA at each applied voltage. The approximated curve reaches 1.0 m/s at \( V_{\text{pp}} = 7.5 \text{ kV} \) and exceeds 2.5 m/s at \( V_{\text{pp}} = 10 \text{ kV} \).

![Fig. 3 Configurations of the experimental PA in bird’s-eye and cross-sectional views. The PA consists of two electrodes (copper foil tape) and a dielectric layer (polyimide film). A high voltage sinusoidal wave is applied to the top electrode.](image)

2.4 Measurement method

To investigate the effects of flow control using the PA on the aerodynamic drag and flow field around the model, we measured the aerodynamic force, surface pressure, and velocity distribution through tests conducted in the wind tunnel facility. The aerodynamic force \( F_x \), in the longitudinal direction of the model was measured by a three-component balance (NISSHO-ELECTRIC-WORKS, LMC-3501-100N). To calculate the aerodynamic drag coefficient \( C_D \), the measured force was non-dimensionalized by the dynamic pressure at the center of the measurement section and at the frontal area of the model. Time-averaged force was measured for 30.0 s and the sampling frequency was set to 1.0 kHz. The pressure on the model surface was measured using a compact pressure scanner (Scanivalve, MPS4264). Stainless pipes with 0.8 mm inner diameter were embedded into the model surface to act as pressure holes, and each pipe (extending into the inside space of the model) was connected to the pressure scanner by a urethane tube. The differential pressure from the reference pressure (the static pressure of a Pitot tube located at the nozzle exit) was measured. Measurements were conducted three times for 5 s with a sampling rate of 10 Hz for each model and applied voltage. The flow field around the model was measured as the velocity vector distribution on a cut-plane located 50 mm behind the model using a dynamic 4-hole pressure probe (TFI, Cobra Probe). The dynamic 4-hole pressure probe was fixed to a three dimensional traverser in the test section, and the velocity vectors at a total of 255 points at 5 mm intervals on the cut-plane (70 mm height × 80 mm width) were measured. The velocity vectors were measured for 4.0 seconds with sampling rates of 2.0 kHz. Comparison of the results with and without the probe for the flow field measurements confirmed that the probes and the traverser did not affect the aerodynamic force.

Figure 5 shows the dependency of \( C_D \) on the Reynolds number \( Re_L \), based on the model length. The values of \( C_D \) in Fig. 5 are normalized by \( C_{D_{Ref}} \), which is the \( C_D \) value at the maximum wind speed of 22 m/s corresponding to \( Re_L = 1.3 \times 10^6 \). \( C_D \) decreases with increasing \( Re_L \) when \( Re_L < 1.0 \times 10^6 \), and is constant when \( Re_L > 1.0 \times 10^6 \). To relatively increase the momentum induced by the PA, we set the wind speed to be lower than the maximum wind speed achievable within the high Reynolds number range (where the \( C_D \) is constant). Therefore, in this study, all measurements were conducted at \( Re_L = 1.20 \times 10^6 \), corresponding to a uniform flow velocity in the wind tunnel of approximately 20 m/s. We applied three voltages (7.5 kV, 8.5 kV, and 9.5 kV) to the PA for the aerodynamic force.
measurements. We found that we had to lower the maximum voltage from 9.5 kV to 9.1 kV for the surface pressure measurements to sustain the life-time of the actuator for the longer measurements. For this reason, we only applied 9.1 kV in the velocity measurements. Measurements without PA actuation were also taken for comparison purposes.

Fig. 4  Maximum induced flow velocity \( U_{\text{max}} \) at each peak-to-peak value of the applied voltage \( V_{PP} \) (points) and its approximated curve (solid line). Flow velocity was measured using a single PA unit mounted on a flat plate.

Fig. 5  Dependence of the drag coefficient \( C_D \) on the Reynolds number \( Re_L \) based on the model length. The \( C_D \) is normalized by the value at the maximum wind speed condition (\( Re_L = 1.30 \times 10^6 \)).

3. Experimental results

3.1. Aerodynamic effect of the curvature radius of the rear corner

We measured the aerodynamic drag force acting on the three models with different curvatures at the rear-end corners. In these measurements, the PA was not installed on any model. Figure 6 shows the measured \( C_D \) of each model, indicating that the \( C_D \) value decreases as the curvature decreases. This tendency is consistent with known automobile aerodynamics, as mentioned in the Introduction. Here, the \( C_D \) of the edge model was 6% lower than the base model, and we consider this 6% value as the target drag reduction rate using PA actuation while preserving the rounded shape at the rear corners.

To clarify the cause for the differences in aerodynamic drag among the models, we measured the surface pressure distribution on the rear end of the base and edge models. Figure 7 shows the pressure distributions of the two models when viewing the vehicle from the rear. The pressure measured at 105 and 95 points for the edge and base models respectively, and their locations are drawn as black dots and intersections of black lines in Fig. 7. The base model experiences a lower surface pressure on the rounded corner, especially in the upper portion, compared to the edge model. As a quantitative evaluation, we calculated drag forces caused by the pressure distribution on the rear-end corners and the base surface by a numerical integration. \( C_{D,C} \) and \( C_{D,B} \) are normalized drag coefficients of these components on the corner and the base surface, respectively, and their values are written in Fig. 7. The difference of \( C_{D,C} \) between the base and edge model is 0.06 and it corresponds to the difference of the total \( C_D \). This indicates that the difference in aerodynamic drag depending on the curvature radius is caused by the difference in the surface pressure on the rear-end corner. Nakano et al. (2017) conducted aerodynamic simulations of these two models and pointed out the effect of the longitudinal vortices generated at both ends of the trunk deck as the cause for the surface pressure difference. As shown in Fig. 8, a pair of upper and lower longitudinal vortices are generated on both sides of the model (one side is shown in the figure). The upper vortex is generated at the rear pillar and the lower vortex, separated from the side end of the trunk deck, is caused by the downward flow from the roof impinging on the trunk deck (hereinafter, these are referred to as a rear-pillar vortex and a trunk-deck-end vortex, respectively). In the base model, as the trunk-deck-end vortex flows closer to the rear-end corner of the model, the negative pressure at the center of the vortex decreases the surface pressure at the upper side of the corner. Furthermore, the vortex supplies momentum to the boundary layer on the body side surface, thereby suppressing flow separation from the rear-end corner (which we wish to avoid), and the flow along the rounded surface decreases the surface pressure because of the Coanda effect. These two phenomena cause the increase of \( C_D \) in the base model because of the pressure drop experienced at the rear-end corners. Therefore, we evaluated how to control the trunk-deck-end vortices causing both the phenomena by applying the proposed PA actuation scheme.

With regard to flow control of the longitudinal vortex using PA, Hasebe et al. (2011) studied suppression of wing tip vortices. They applied PA to induce flow near the origins of the vortices, and it improved the wing performance by
reducing the circulation and the radius of the vortices. Nakano et al. (2017) numerically investigated the application of a similar flow control approach to suppress the trunk-deck-end vortices of the base model being evaluated in this study. Although it was possible to reduce the \( C_D \) by inducing flow near the origins of the trunk-deck-end vortices, an induced flow of higher magnitude than the mainstream was necessary to accomplish drag reduction. Thus, in this study, we did not consider suppressing the trunk-deck-end vortices. Instead, we considered suppressing the pressure drop by promoting flow separation at the rear-end corners by keeping the vortex at each corner away from the model in the \( Z \) direction. Figure 9 shows the PA set-up mounted at the upper sides of the rear-end corners of the model, where strong negative pressure due to the central low pressure of the trunk-deck-end vortices was observed. To induce greater momentum and faster flow (Thomas et al., 2009), two PA units were mounted in parallel on each corner symmetrically, such that the distance between their top electrodes was 10 mm. In order to promote flow separation from each corner, we induced flow in the opposite direction of the mainstream by actuating the PA. Thus, we set the directions of the PAs as shown in Fig. 9 to induce flow toward the upper and outside ends of the model.

![Fig. 6 Influence of the curvature at a rear-end corner on the drag coefficient \( C_D \). The \( C_D \) values are normalized by the base model value. The drag coefficient is reduced for smaller curvatures in this model.](image)

![Fig. 7 Surface pressure distribution comparison. Top and bottom figures show bird’s-eye and back views, respectively. Compared with the edge model, the base model exhibits low surface pressure at the rear-end corners, especially in the upper areas. Black dots and intersections of the black lines on the distributions represent measurement points. \( C_{D,C} \) and \( C_{D,B} \) in the bottom figures are drag coefficients evaluated by numerical integration of the pressure distributions at the corners and base, respectively.](image)

![Fig. 8 Schematic image of flow around a rear-end corner. The edge model produces flow separation at the corner. The base model produces flow from the side of the body into the wake area along with the trunk-deck-end vortex.](image)

![Fig. 9 Installed positions of parallel pairs of PAs and induced flow directions (upper blue arrows). Each PA pair is mounted on the rounded surface along the lower pressure area and flow is induced in the direction opposite to the mainstream.](image)

### 3.2 Aerodynamic drag reduction by PA actuation

The effect of the PA actuation on aerodynamic drag was investigated next. Figure 10 shows the \( C_D \) normalized by \( C_{D,OFF} \), which is the drag coefficient when the PA was not actuated but was mounted on the model, for each applied voltage. The graph also includes the drag reduction rate induced by PA actuation, and indicates that the PA actuation reduces the \( C_D \) and that a higher applied voltage reduces it further. The reduction rate reaches 3% at the highest applied
voltage of 9.5 kV. This reduction rate is significant because it is half of the target reduction rate of 6% achieved by the sharp edge of the rear-end corner. Moreover, the drag reduction rate has not saturated at the highest applied voltage. Hence, it may be possible to reach the same level as the sharp edge by modifying the location and/or the operating conditions of the PA.

![Fig. 10 Dependencies of the drag coefficient $C_D$ (bars) and the drag reduction rate (blue plot) on the applied voltage. The $C_D$ was reduced by the flow control method using the PA setup shown in Fig. 9. A higher applied voltage increases the drag reduction ratio. The drag reduction ratio reaches approximately 3% at the highest applied voltage of 9.5 kV.](image)

3.3 Surface pressure change induced by PA actuation

To clarify the mechanism of the aerodynamic drag reduction achieved by PA actuation, we measured surface pressure distributions around the rear-end corners in the cases with and without PA actuation and compared them. Fifteen taps for surface pressure measurements were installed only at the upstream side of the rear-end corners because we were not able to embed pressure holes on the corners covered by the PA. Figure 11 shows the surface pressure distribution based on applied voltage. Here, we defined the coordinate $z$ as the vertical distance from the trunk deck surface, which is normalized by the height of the trunk part $h$. The figure shows that the lower pressure appears closer to the corner and that PA actuation recovers some of the pressure drop. To provide a quantitative discussion, we defined a pressure recovery rate $R_P$ and a drag reduction rate $R_D$ based on the effect of the sharp edge at the rear corner as follows:

$$R_P = \frac{(C_{P, ON} - C_{P, OFF})}{(C_{P, edge} - C_{P, OFF})} \times 100, \quad (1)$$

$$R_D = \frac{(C_{D, ON} - C_{D, OFF})}{(C_{D, edge} - C_{D, OFF})} \times 100. \quad (2)$$

Here, $C_P$ represents the averaged pressure coefficients of the 15 measurement points located in the same position in all cases. The subscripts $_{ON}$, $_{OFF}$, and $_{edge}$ refer to the values with PA actuation, without PA actuation, and of the edge model, respectively. Figure 12 shows the rates $R_P$ and $R_D$ at each applied voltage. $R_P$ increases with the applied voltage and this trend is consistent with the $R_D$ trend. This agreement in trends indicates that the drag reduction by PA actuation was mainly caused by the pressure recovery at the rear corner, as intended. Furthermore, the pressure recovery by PA actuation increases with the applied voltage, as shown in Figure 12.

![Fig. 11 Surface pressure distributions near the rear end of the body side surface. The pressure recovers owing to the PA actuation. As the applied voltage increases, the low pressure area (blue) decreases.](image)

![Fig. 12 Pressure recovery ratio and drag reduction rate caused by PA actuation. They show similar trends versus the applied voltage.](image)
actuation extends to one-half the height of the trunk part \( (z/h = 0.5) \), where it is not affected by the trunk-deck-end vortices directly. This implies that the pressure recovery shown in Fig. 11 was caused not only by moving the low pressure of each vortex center away from the corner of the body but also by moving the flow separation point upstream in the corner width direction. Additionally, the movement of the flow separation point was qualitatively observed using smoke illuminated by a laser sheet.

### 3.4 Flow field change caused by PA actuation

Finally, from the flow visualizations, we verified the change of the trunk-deck-end vortices directly. Figure 13 shows the distributions of vorticity \( \omega_X \) along the \( X \)-axis behind a rear-end corner in the cases with and without PA actuation. The vorticity \( \omega_X \) was calculated from the velocity components in the \( Y \) and \( Z \) directions measured at the four neighboring measurement points based on the second-order central difference scheme. A pair of longitudinal vortices with opposite vorticity is shown in the figure. The upper vortex with negative vorticity is the rear pillar vortex generated by the separated flow from the rear pillar, and the lower vortex with positive vorticity is the trunk-deck-end vortex. Comparing the two distributions with and without PA actuation, the position of the pair of vortices shifts upward, but the peak values of the vorticity and the sizes of the vortices are not affected by the PA actuation. This indicates that flow control using the PA reduced the aerodynamic drag but did not reduce the trunk-deck-end vortex at each corner, instead moving it upward, as we aimed to accomplish in this study. When the pair of vortices at each corner is shifted upward by PA actuation, each trunk-deck-end vortex is shifted further away from the corner. Thus, the pressure drop on the rear-end corners caused by the low pressure at the vortex center as well as that caused by the attached flow on the corner (the Coanda effect) is reduced, as previously mentioned. Even though the pressure drop could not be reduced completely as in the edge model, the flow field change caused by PA actuation provided a measurable reduction in the drag experienced by the base model.

![Vorticity distribution in the wake area (rear view).](image)

**Fig. 13** Vorticity distribution in the wake area (rear view). (a): PA OFF, (b) PA ON for the case of \( V_{pp} = 9.1 \) kV. A pair of counter rotating vortices is formed by the separated flows from the rear pillar and the side end of the trunk deck (blue and red contours, respectively). Both vortices are shifted upward in the \( Z \) direction by the PA actuation, while their size and peak vorticity are not affected.

### 4. Conclusion

In this study, we applied a dielectric barrier discharge plasma actuator (PA) at the rear end of a simplified automobile model and studied its effects using wind tunnel experiments with the intent of reducing the aerodynamic drag by promoting rather than suppressing flow separation on a curved surface. Focusing on the longitudinal vortex structures that increased the drag at the rear-end corners, we determined the settings of a PA system that could be used to keep these vortices away from the corners.

Through PA actuation, the longitudinal vortices shifted upward to a position located far from the rear-end corner. The surface pressure recovered at each corner because of two types of flow change: the direct effect of the low pressure of the vortex center was reduced by shifting the position of the vortex in the \( Z \) direction, and the flow separation point at each corner moved upstream, which reduced the pressure decrease caused by the Coanda effect. As a result of these flow changes, aerodynamic drag was successfully reduced by up to 3% in the wind tunnel tests. This was approximately half the target rate determined from the sharp-edged rear corner shape.

From these results, the PA has demonstrated its usefulness as a device to improve aerodynamic performance while maintaining design freedom, at least in the scaled model. For further reduction of aerodynamic drag and application to
real automobiles, optimization of the PA set-up according to target flow characteristics and increasing the induced flow velocity are expected to be necessary. For the former, we will further visualize and clarify details regarding the flow changes caused by PA actuation in future work.

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