

Aerodynamic Development for High-speed Stability in New CIVIC

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ABSTRACT

Aerodynamic design for the new model CIVIC sought to reduce aerodynamic drag and help ensure vehicle stability at high speeds. Equivalent lift was employed as an evaluation index expressing the effect of aerodynamic forces on vehicle dynamic performance, and the importance of reducing rear equivalent lift in helping to ensure stability was verified in driving test measurements. In order to reconcile the reduction of rear equivalent lift with low drag, the control of longitudinal vortices at the rear of the vehicle was set as a goal, with measures adopted in both the platform and the exterior. The realization of increased underfloor flow velocity through the use of underfloor devices and the aerodynamic engineering of the exterior side-view profile and the area around the rear pillars reduced rear equivalent lift by approximately 50% against the previous model. This has limited changes in rear tire performance with changes in vehicle speed, and helped to ensure vehicle stability in the high-speed range.

1. Introduction

It is well known that aerodynamic performance fulfills important functions for racing vehicles. At the same time, there is a tendency to believe that because the effect of aerodynamic performance on mass-production vehicles is much lower than on racing vehicles, that aerodynamics does not have a particularly strong effect on vehicle stability in these cases. In fact, however, the aerodynamic forces acting on mass-production vehicles, including the effect of cross winds, are not insignificant enough to be ignored.

In the case of racing vehicles, aerodynamic devices are attached to the vehicles to generate downforce and increase the vertical load on the tires, thus increasing the lateral force, in order to increase cornering speed.

However, in mass-production vehicles, it is generally the case that shapes that generate lift are employed in order to make it possible to realize functional demands in the normal use range and to satisfy styling demands. Because this results in a decline in the vertical load and a consequent decline in the lateral force on the tires when vehicle speed increases, it tends to result in reduced stability.

In particular in the area of vehicle stability at high speed, differing aerodynamic specifications will produce differences able to be felt by the driver; aerodynamic force control represents an important element in vehicle

dynamics. Many questions remain to be answered in the field of high-speed vehicle stability in response to aerodynamics in the high-speed range. The research focus is expanding from steady-state flows to include non-steady-state flows, and a good deal of research is being conducted on flow fields resulting from disturbances produced by natural wind⁽¹⁾.

The necessity to realize low drag (low CD) has increased within the development process for mass-production vehicles in order to satisfy today's intense demand for competitiveness in the area of fuel efficiency, and it is not easy to reconcile this with high-speed vehicle stability. In addition, the inputs resulting from aerodynamic forces represent an element in the system characteristics (including the tires and suspension), making it challenging to set separate target values for aerodynamics.

The development of the new model CIVIC was therefore conducted with consideration for reconciling high-speed vehicle stability with the realization of a low CD in order to achieve a high level of fuel efficiency from the initial stages of the platform development process. This paper will discuss the aerodynamic methods used to reconcile target high-speed vehicle stability with low CD in the development of the new model CIVIC from the perspectives of platform development and exterior development.

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2. Aerodynamic Vehicle Stability Goals for New Model CIVIC

The dynamic performance concept for the new model CIVIC was the realization of outstandingly agile linear performance and a feeling of stability. Aerodynamic force control in the high-speed range would be an important element in balancing agile handling in the low-speed range with a feeling of stability in the high-speed range.

In order to realize a feeling of stability at high speeds, it would be necessary to achieve improvements in basic indices of dynamic performance, for example steady-state yaw rate gain and lateral acceleration phase delay at high speeds.

The concept of equivalent CL , which encompasses the effects of lift and side force, was introduced as an evaluation index that links these indices of dynamic performance and steady-state aerodynamic forces^{(2), (3)}.

The goal during the development of the new model CIVIC was to clarify the contribution of front and rear equivalent CL to dynamic performance, to substantiate the effectiveness of the index on vehicle dynamics through actual vehicle measurements, and to balance the target equivalent CL with low CD .

3. Contribution of Equivalent CL to Dynamic Performance

3.1. Formularization of High-speed Vehicle Stability and Aerodynamic Forces

Aerodynamic forces act on the aerodynamic center of the vehicle body as drag, lift, and side force. These forces are supported by the contact patches of the front and rear wheels, via the suspension. Understanding the contribution to the tires is an important factor when considering the effect of aerodynamic forces on vehicle stability. Cornering power (CP) is the lateral force generated on the tire per unit slip angle, and is employed as an index of basic tire performance. Figure 1 shows the relationship between CP and the vertical load on the tires. Here, K is tire CP, and

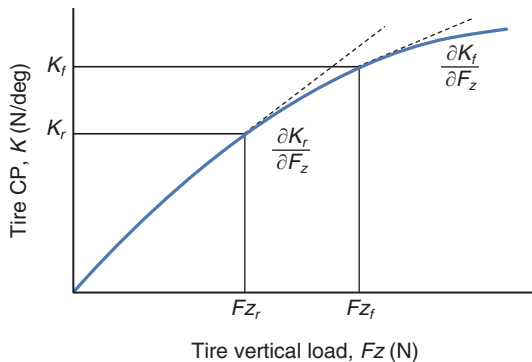


Fig. 1 Tire CP and vertical load for FF car

F_z is the vertical load on the tires. The subscripts f and r respectively refer to front and rear. Tire CP displays a nonlinear characteristic in relation to load. In an FF vehicle like the CIVIC, the allocation of load is further towards the front than the rear, and because of this the vertical load on the rear tires is lower than that on the front tires. Rear CP is therefore prone to change in response to changes in vertical load.

Assuming steady-state cornering, the effect of aerodynamic forces including side force can be understood as the fluctuation in the vertical load that produces change in the lateral force on the tires. Eq. (1) shows the change in tire CP due to aerodynamic forces. Here, ρ is air density, V is vehicle speed, A is the frontal projected area of the vehicle, CL is the lift coefficient, CS is the side force coefficient, and CYM is the yaw moment coefficient.

$$\Delta K_i = -\frac{1}{2} \cdot \frac{1}{2} \rho V^2 A \cdot CL_i^* \cdot \frac{\partial K_i}{\partial F_z} \quad (i=f \text{ or } r) \quad (1)$$

In this equation, $*$ represents equivalent CL , a hypothetical lift coefficient that expresses the effect on the tires, including CS and CYM .

$$\begin{aligned} CL_f^* &= CL_f + (\Delta CL)_f^{CS, CYM} \\ &\cong CL_f - \frac{\partial CS_f}{\partial \beta} \frac{l_f K_f}{l_r K_r} \bigg/ \frac{\partial K_f}{\partial F_z} \end{aligned} \quad (2)$$

$$\begin{aligned} CL_r^* &= CL_r + (\Delta CL)_r^{CS, CYM} \\ &\cong CL_r - \frac{\partial CS_r}{\partial \beta} \bigg/ \frac{\partial K_r}{\partial F_z} \end{aligned} \quad (3)$$

$$CS_f = \frac{CS}{2} + CYM, \quad CS_r = \frac{CS}{2} - CYM \quad (4)$$

Here, β represents the slip angle of the vehicle body. CS_f and CS_r respectively represent the front and rear side force coefficient. These coefficients express the allocation of side force to the front and rear tires by the yaw moment.

The contribution of CS and CYM to equivalent CL is around at least 10%. The improved correlation between the magnitude of equivalent CL and sensory evaluations has been verified by study of CS and CYM based on past evaluations offered by drivers in tests using actual vehicles⁽³⁾.

The effect of equivalent CL on vehicle dynamics will be considered using the stability factor, an indicator of vehicle stability. The stability factor, K_s , is defined by Eq. (5).

$$K_s = -\frac{m}{2l^2} \frac{l_f K_f - l_r K_r}{K_f K_r} \quad (5)$$

Here, m is the vehicle mass, l is the wheelbase, and l_f and l_r are the respective distances from the center of gravity

to the front and rear axles.

Generally, the higher the stability factor, the more the vehicle displays an understeer characteristic, and the greater the stability of the vehicle. Figure 2 shows an example of the relationship between tire CP and the stability factor in relation to vehicle speed when equivalent CL is acting uniformly on the front and rear tires. Taking into consideration the load-dependency of tire CP discussed above, in an FF vehicle rear tire CP tends to be particularly affected by equivalent CL_r . Therefore, despite the fact that the same equivalent CL is acting on the front and rear tires, i.e. the reduction of vertical load is the same for the front and rear tires, the amount of change in tire CP will differ for the front and rear tires. Because of this, the stability factor declines with increasing vehicle speed, and the vehicle tends to display an increasing tendency towards oversteer as vehicle speed increases. This can also be considered as aerodynamic forces acting to make tire CP dependent on velocity. Reducing the effect of this characteristic was the target for high-speed vehicle stability in this development.

3.2. Equivalent CL and Handling Indices

As in the case of the stability factor, the basic characteristics of the vehicle dynamic system change with changes in front and rear tire CP produced by equivalent CL . These changes appear as changes in handling indices, which express the dynamic maneuverability and stability of the vehicle in relation to yaw. Standard handling indices include steady-state yaw rate gain, yawing resonance frequency, and handling capacity. These are used, respectively, as indices to express the magnitude of yaw angle velocity, responsiveness, and convergence of transient response in relation to steering, and can be expressed using front and rear tire CP⁽⁴⁾.

When a vehicle is driving at high speeds, it is desirable

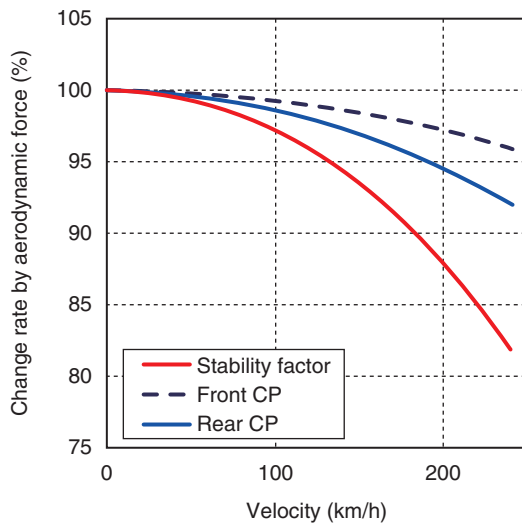


Fig. 2 Velocity dependency of stability factor and tire CP in relation to aerodynamic forces

that its yaw dynamics should be constrained in relation to slight steering input, that the vehicle should respond instantaneously to corrective steering, and that its dynamic behavior should converge rapidly following corrective steering. It is desirable therefore that the yaw rate velocity should be low, that responsiveness should be high, and that the convergence of transient response should be rapid.

Figure 3 shows isolines of the handling indices in relation to equivalent CL (which provides a standard) and desirable directions for equivalent CL during high-speed driving. When the realization of a balance between stability and a good transient response characteristic is set as the target, the desirable direction for equivalent CL_f differs for each of the indices, and cannot be uniquely determined. By contrast, a reduction in CL_r is the desirable direction in the case of all the indices. This is because rear tire CP increases with a reduction in equivalent CL_r , indicating the importance of maintaining high rear CP for vehicle dynamics. An increase in the rear tire CP in the high-speed range alone would not be manifested as a change in the suspension characteristic. It was therefore considered that reducing equivalent CL_r would represent an effective means of boosting straight-line stability in the high-speed range.

3.3. Actual Driving Tests Using Different Equivalent CL_r

Actual driving tests were conducted in order to study the effectiveness of reducing equivalent CL_r in increasing high-speed vehicle stability.

Aerodynamic devices were fitted to vehicles in order to produce two specifications with differing equivalent CL_r (Aero Configuration A and Aero Configuration B). Measurements were conducted in order to determine how these different aerodynamic configurations would change the steering response of an actual vehicle. Figure 4 shows wind tunnel measurements of equivalent CL and the change in tire CP at 180 km/h when switching from Aero Configuration A to Aero Configuration B. Equivalent CL_r is lower for Aero Configuration B than for Aero Configuration

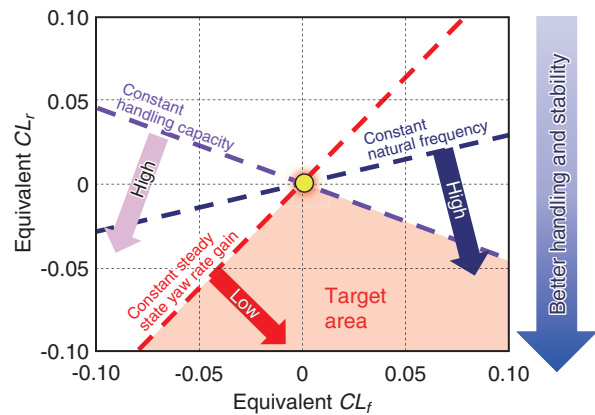


Fig. 3 Preferable directions for equivalent CL_f and CL_r in terms of handling indices

A [Fig. 4(a)]. Because of this, rear tire CP at 180 km/h is more than 3% higher for Aero Configuration B than for Aero Configuration A. By contrast, the change in front tire CP is less than 1% [Fig. 4(b)]. It may therefore be considered that the difference in measurement results with the change in the aerodynamic specifications originates in change in rear tire CP, in other words change in equivalent CL_r .

Figure 5 shows measurement results for yaw rate gain and lateral acceleration phase delay for the two aerodynamic configurations. These measurement results, taken in an actual vehicle, show that in the high-speed range, the change from Aero Configuration A to Aero Configuration B reduces steady-state yaw rate gain by approximately 10% and lateral acceleration phase delay by approximately 14%. This meant that the hypothesis that reducing equivalent CL_r would be effective in maintaining high-speed vehicle stability was supported by the results of actual vehicle measurements. Equivalent CL_r was therefore focused on in the development of the new model CIVIC.

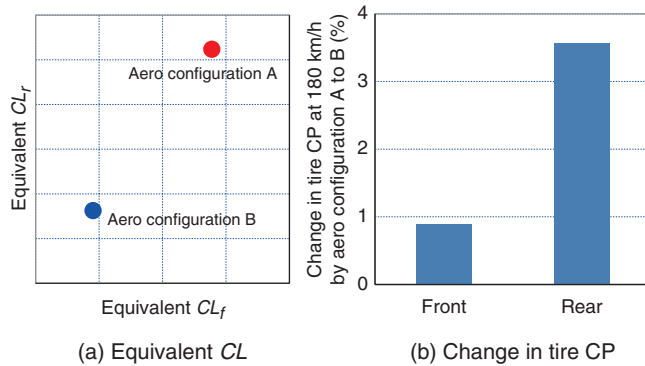


Fig. 4 Difference in equivalent CL between two aerodynamic configurations and its effect on tire CP

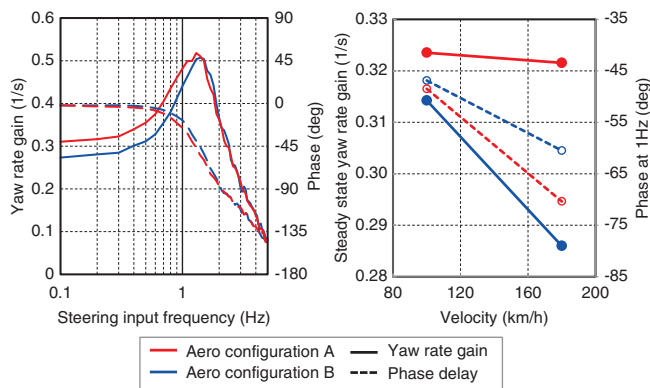


Fig. 5 Results of steering response tests using two aerodynamic configurations

4. Balancing Low Equivalent CL_r and Low CD

Based on Eq. (3), increasing CS_r/β , reducing CL_r , and controlling the degree of reduction in rear tire CP when the tire load was reduced could be considered as methods of reducing equivalent CL_r . It was therefore necessary to increase CS_r/β and reduce CL_r by modifying the vehicle's aerodynamic characteristics.

The greatest advantage of the introduction of the concept of equivalent CL was that multiple objective functions (front and rear CL , CS , and CYM) could be aggregated into front and rear equivalent CL . At the stage of optimization of the actual shape of the vehicle, there would thus be no necessity to consider a breakdown of these functions; it would be sufficient to focus on reducing equivalent CL .

At the same time, fixing the concept for the flow field in order to realize the various aerodynamic characteristics set as aims for the development is an important factor in aerodynamic development. This section will introduce the aerodynamic concepts and approaches employed to realize an increase in CS_r/β and a reduction in CL_r .

4.1. Increased CS_r/β

Increased CS_r/β would mean reduction of the aerodynamic yawing moment, and could be realized by increasing CS and reducing CYM . However, because increasing CS might reduce stability in cross winds, it would be desirable to achieve a reduction in CYM without increasing CS .

Figure 6 shows CFD results for changes in CS and CYM produced by different exterior changes and underfloor devices. Underfloor devices produce only small changes in CS and CYM , of 5% or less. It was therefore considered that the effect of the platform and underfloor devices on CS and CYM could be ignored.

In the case of exterior changes, changes to the basic

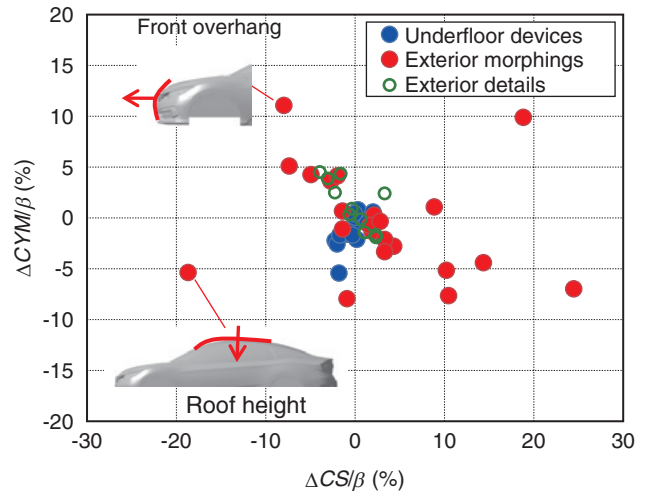


Fig. 6 CFD prediction of changes in CS and CYM by various aerodynamic features of prototype car

dimensions that determine the framework, including overhang and total height, i.e. major changes to the basic package, produce major changes in CS and CYM . However differences in the shape of the vehicle introduced at the stage of optimization of the detailed aerodynamic shape produce only small changes.

4.2. Reduced CL_r

4.2.1. Reduction of CL_r in platform development

Figure 7 shows the aerodynamic concept for the new model CIVIC, formulated in order to balance reduced equivalent CL_r and low CD . This concept involved accelerating the underfloor flow in order to create an upward flow (upwash) and controlling the downward flow (downwash) on the vehicle exterior in order to control longitudinal vortices at the rear of the vehicle. Control of rear longitudinal vortices was expected to correct the growth of uneven left-right longitudinal vortices when a yaw angle is produced, in addition to improving the aerodynamic yaw characteristic.

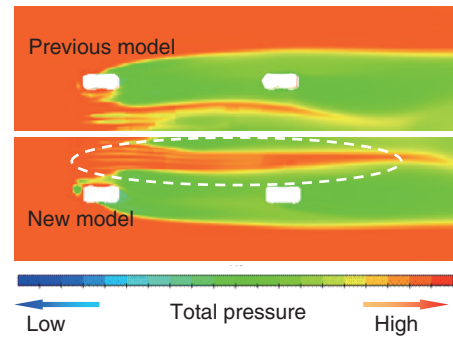
From the stage of platform development, the area for application of aerodynamic undercovers was expanded across the entire vehicle, and the parts on which aerodynamic covers would not be used, including the rear suspension, the heat baffles, and the silencer, were comprehensively smoothed in order to accelerate the underfloor flow. Figure 8 shows the underfloor shape of the new model CIVIC.

Figure 9(a) shows differences in the total pressure distribution under the floor between the previous and the new models, and 9(b) shows a comparative diagram of the velocity fields around the underfloor sections of the two models. The smoothing of the parts from the engine undercover and floor cover to the rear bumper has increased the ratio of the high-pressure areas in the flow that travels from between the front tires and exits at the rear of the vehicle in the new model against the previous model [Fig. 9(a)]. In other words, flow velocity does not decline before the rear of the vehicle, indicating that it has been possible

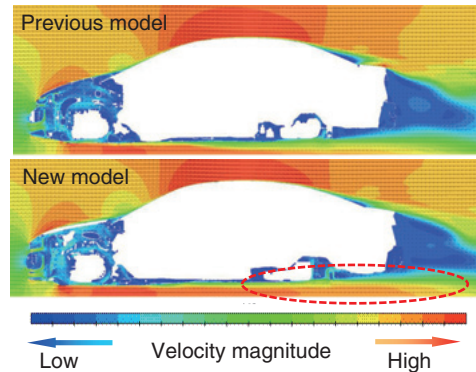
to accelerate the underfloor flow [Fig. 9(b)]. These results demonstrate that reduced CD has been reconciled with reduced CL_r under the floor without antagonistic results.



Fig. 8 Aerodynamic treatment on new CIVIC underfloor



(a) Total pressure distribution at $Z=100$ mm



(b) Velocity distribution throughout underfloor

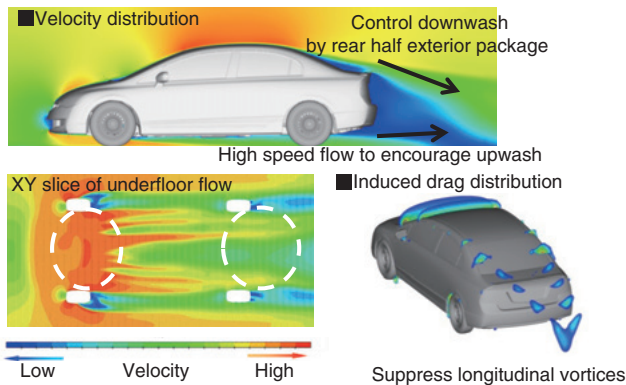


Fig. 7 Aerodynamic concept developed to balance low equivalent CL_r with low CD

Fig. 9 Difference in flow under floor between new and previous model platform

4.2.2. Exterior aerodynamic concept

Compared to the underfloor flow, which is affected by factors including the tires, differences in level between parts, and the hot air emitted by the engine housing, the flow around the exterior of the vehicle encounters few shapes that would produce loss, and flow velocity is high. The flow around the exterior therefore has the dominant effect on the flow field for the vehicle as a whole.

Three measures were applied in the exterior development process in order to realize reductions in both CL_r and CD .

The first of these was to pinch up the front edge of the hood, emphasizing the edge only to the degree that separation would not be generated, and inducing suction in this section.

The second approach, in line with the pinching up of the front edge of the hood, was to move the roof peak forward, in order to move the area of suction on the roof forward.

The third measure was to reduce the depth of the angle of the side view by shifting the base of the C-pillar to the rear in order to control downwash at the rear of the vehicle.

The first two approaches will be considered first. Pinching up the front edge of the hood and moving the roof peak forwards in order to shift the area of suction generated in the upper half of the vehicle towards the front and produce a pitch-up moment resulted in a comparative reduction in CL_r .

Because it is positioned at the front extremity of the vehicle, changes in the shape of the front edge of the hood in particular promote change in the pressure peak and longitudinal shift in the center of pressure. It is therefore one area that will tend to produce change in the front-rear balance of CL .

Figure 10 shows an example of change in the pressure coefficient and change in front-rear CL when the front edge of the hood is pinched up. Changing the shape of the front edge of the hood to the shape shown by the white line changes the pressure distribution around the hood, and the area of low pressure shifts towards the front by comparison with the original shape. Thus, although there has been no change in CL itself, the center of pressure, shown by the red arrow, has shifted to the position shown by the blue arrow, and the pitch-up moment acting on the center of the vehicle has increased. This shifts the front-rear distribution of CL towards the front, with the result that the pinching up of the

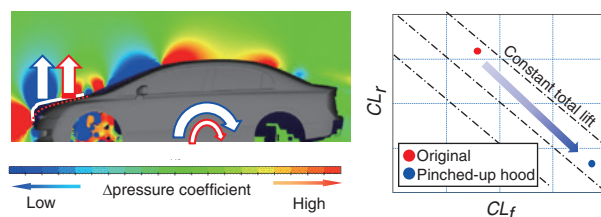


Fig. 10 Pressure difference and CL balance shift by pinching up front end of hood

front edge of the hood reduces CL_r .

While the degree will differ, moving the roof peak forwards can also be expected to have a similar effect.

Figure 11 shows the difference between the shape of the new and the previous models. Figure 12 shows the difference in the pressure coefficient. The forward shift in the pressure distribution shown in Fig. 10 can be seen in the change in pressure shown by the solid line in Fig. 12, and it was therefore considered that CL_r had been reduced.

In addition to this, moving the roof peak forwards reduced the change in the rate of curvature of the roof from the roof peak to the rear window, facilitating pressure recovery. This has controlled the generation of boundary layers and the occurrence of separation due to strong adverse pressure gradients at the rear edge of the roof, as shown by the broken lines in Fig. 12. The maintenance of a high-velocity flow up to the rear of the trunk is considered to have increased control of downwash (Fig. 13).

The shifting of the C-pillar to the rear will now be



Fig. 11 Side view comparison of new and previous models

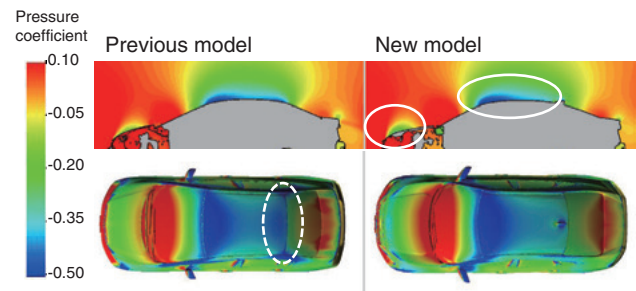


Fig. 12 Difference in pressure coefficient distribution by hood and roof profiles

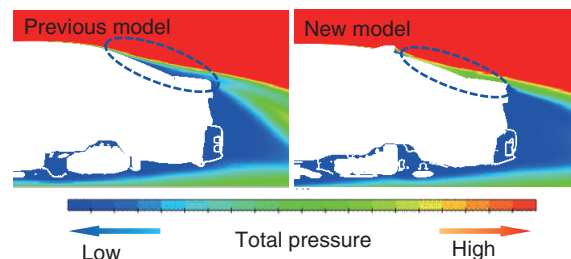


Fig. 13 Change in flow separation around rear window

considered. Figure 14 shows the difference in the shape around the C-pillar between the new and previous models.

Figure 15 shows the pressure distribution around the C-pillar for the new and previous models.

As Fig. 15(a) shows, in the previous model not only was suction strong around the C-pillar, but, as noted above, it was also strong at the rear edge of the roof, producing variations in pressure distribution around these areas. By contrast, in the new model, suction is weak around both the C-pillar and the rear edge of the roof, and there is a minimal pressure differential with the surrounding area. This indicates that shifting the base of the C-pillar to the rear made the surface pressure distribution around the C-pillar uniform.

Figure 15(b) shows the pressure distribution on the surface of the vehicle for a cross-section at the rear edge

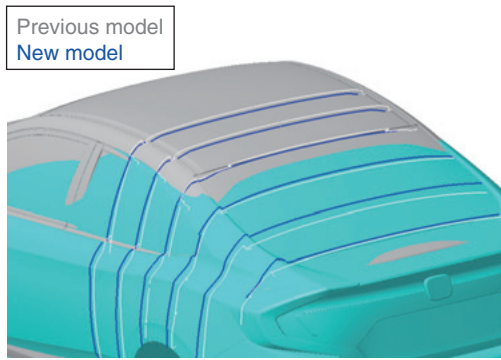
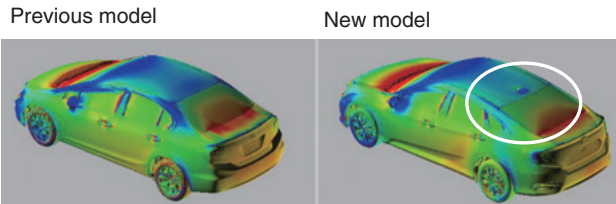
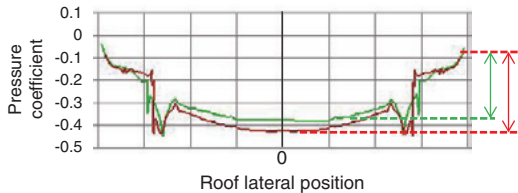


Fig. 14 Shallower inclination of C-pillar on new model



(a) Uniformity of pressure coefficient in rear end of new model



(b) Pressure difference between C-pillar and roof

Fig. 15 Difference in pressure coefficient around C-pillar

of the roof. In the new model, there is a minimal pressure difference between the side face of the pillar and the rear edge of the roof. If this pressure difference were high, it would represent the point of origin of a flow from the side face of the vehicle to the rear edge of the roof, and the downwash would wrap around the C-pillar and form a longitudinal vortex. By creating a uniform pressure distribution around the pillar, the C-pillar shape in the new model controls the rolling-in from the side face of the vehicle to the center that might wrap around the C-pillar and form the point of origin for longitudinal vortices at the rear of the vehicle. The velocity component from the side face of the C-pillar towards the vehicle center has been reduced in the new model (Fig. 16).

The shape from the C-pillar to the trunk in particular has become a design icon of the new model CIVIC, presenting the shape of a sedan but offering the image of a coupe depending on the angle from which it is viewed. In this section of the vehicle, design demands and aerodynamic performance reached an even more sophisticated level of balance.

These modifications of the form of the vehicle and the realization of increased underfloor flow velocity have controlled downwash and the rolling-in from the side of the vehicle, suppressed the formation of longitudinal vortices at the rear of the vehicle, and balanced reduced CD with reduced CL_r .

Figure 17 shows the difference in longitudinal vortices at the rear of the vehicle between the new and previous models. Figure 17(a) shows the distribution of vorticity in the direction of the main flow at the rear of the vehicles, demonstrating that the vortices formed at the rear of the new model have decreased. As a result, the distribution of induced drag, which expresses the drag component produced by longitudinal vortices, has also been reduced [Fig. 17(b)].

The measures discussed above have made it possible to realize a reduction of approximately 50% in equivalent CL_r in the new model CIVIC against the previous model. Figure 18 shows a comparison of equivalent CL_r in the new and previous models and a breakdown of the components of equivalent CL_r . The CL_r and CS_r terms in this breakdown are the first and second terms respectively on the right-hand side of Eq. (3). Pursuing development with a focus on

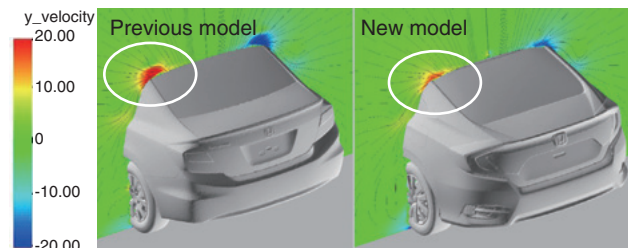


Fig. 16 Y-velocity difference around C-pillar

reducing equivalent CL_r , not only made it possible to reduce CL_r , but also to increase CS_r . This has reduced the decline in rear tire CP due to speed by approximately 50% against the previous model (Fig. 19).

CD has also been reduced by 14% against the previous model. Aerodynamic specifications were developed that provided the potential for the realization of a balance between the target, reduced equivalent CL_r , and low drag.

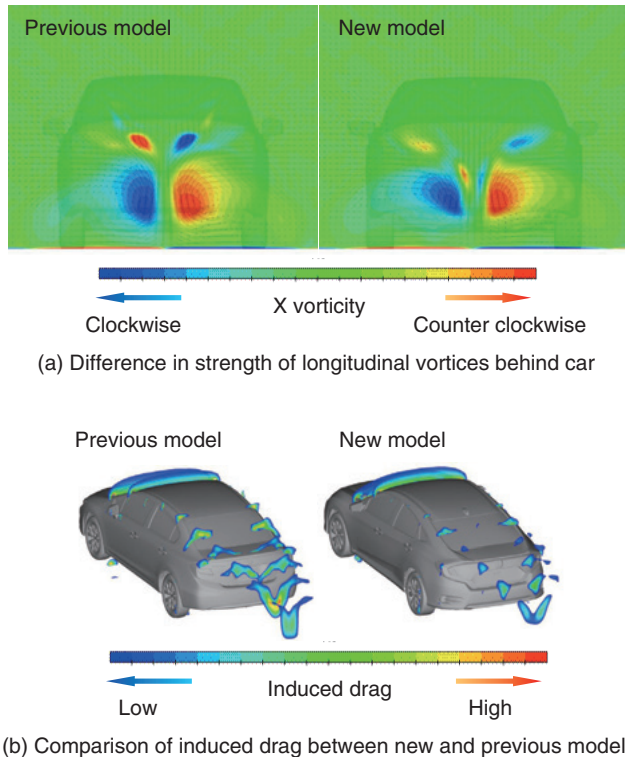


Fig. 17 Suppression of growth of longitudinal vortices for new CIVIC

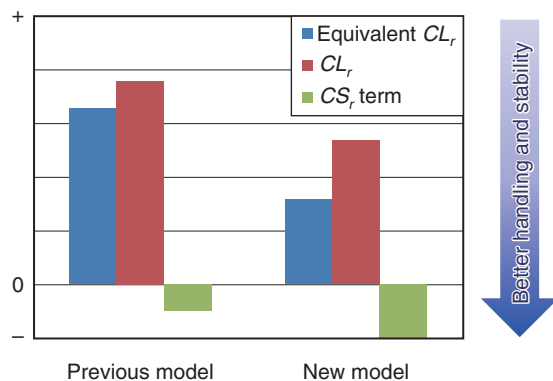


Fig. 18 Comparison of equivalent CL_r between new and previous models

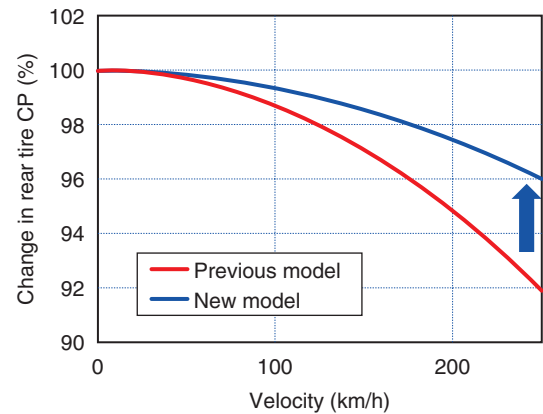


Fig. 19 Comparison of velocity dependency of rear tire CP between new and previous models

5. Conclusion

The development process seeking to realize high-speed stability in the new model CIVIC can be summarized as follows:

- (1) Equivalent CL was employed as an index during the development process, and development focused on reducing equivalent CL_r in order to improve high-speed handling indices.
- (2) The hypothesis regarding the effect of equivalent CL_r on straight-line stability at high speeds was supported by quantitative evidence obtained from measurements conducted in actual driving tests.
- (3) The control of the formation of longitudinal vortices at the rear of the vehicle was addressed as a method of balancing a reduction in equivalent CL_r and a reduction in CD . Aerodynamic specifications capable of mass production were realized in both the new platform and the vehicle exterior.

In future, it will be necessary not only to further elucidate the mechanisms by which aerodynamic forces, including non-steady-state forces, affect vehicle behavior, but also to propose solutions via forms able to be mass-produced. It will also be essential to reconcile any measures with the realization of low drag. The authors therefore wish to comprehensively enhance aerodynamic design capability, including approaches to the feasibility of designs.

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