

Improvement in Vehicle Motion Performance by Suppression of Aerodynamic Load Fluctuations

Mitsuyoshi Kawakami and Osamu Murata
Toyota Central R&D Labs., Inc.

Kazuhiro Maeda
Toyota Motor Corporation

ABSTRACT

This study focuses on fluctuations in the aerodynamic load acting on a hatchback car model under steady-state conditions, which can lead to degeneration of vehicle motion performance due to excitation of vehicle vibrations. Large eddy simulations were first conducted on a vehicle model based on a production hatchback car with and without additional aerodynamic devices that had received good subjective assessments by drivers. The numerical results showed that the magnitudes of the lateral load fluctuations were larger without the devices at Strouhal numbers less than approximately 0.1, where surface pressure fluctuations indicated a negative correlation between the two sides of the rear end, which could give rise to yawing and rolling vibrations.

Based on the numerical results, wind-tunnel tests were performed with a 28%-scale hatchback car model. An antisymmetric flow structure with weak periodicity became apparent from simultaneous measurements of the streamwise velocity fluctuations in the near-wake region and the time-dependent yawing moment. Delta-winglet vortex generators (VGs), which have been widely adopted as separation control devices, mounted on each side of the rear end provided a marked reduction in lateral load fluctuations without a pronounced effect on the time-averaged longitudinal load, although the negative correlation was still prominent.

The delta VGs were then applied to an actual hatchback car and resulted in higher subjective ratings during a track test. This is a promising result that supports the hypothesis that suppression of aerodynamic load fluctuations improves vehicle motion performance.

CITATION: Kawakami, M., Murata, O., and Maeda, K., "Improvement in Vehicle Motion Performance by Suppression of Aerodynamic Load Fluctuations," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(1):2015, doi:10.4271/2015-01-1537.

INTRODUCTION

Unsteady aerodynamic loads acting on a passenger car in a fluid at rest include transient loads associated with vehicle motions and also fluctuating loads arising from the unsteady wake, which are to be found even under steady and straight driving conditions. The former has been of increased interest in the automotive industry (for recent studies, see Refs. [1, 2, 3, 4]), whereas the latter has not been addressed sufficiently from the viewpoint of vehicle stability and maneuverability.

Although the identification of unsteady near-wake structures for bluff bodies in ground proximity has been studied for many years, most of these studies were related to longitudinal load fluctuations in part with the aim of drag reduction. Duell and George [5] experimentally observed repeated vortex pairing along the separated shear layer behind a simplified square-back car model with sharp rear corners. They explained that eventual vortex shedding at the free stagnation point drove periodic bubble pumping at a Strouhal number (St) of

0.069 (based on the model height or width), which resulted in periodic base pressure fluctuations. The results of a corresponding numerical simulation were reported by Krajnović and Davidson [6].

On the other hand, Nouzawa et al. [7] examined the near-wake region of a sharp-edged notchback car model, which was distinct in that it had slanted rear pillars. They clarified the existence of an arch vortex, trailing vortices, and moreover, the periodic fluctuation of the former at around 20 to 30 Hz ($St = 0.32$ - 0.47 , based on the model height). For a more realistic notchback car model, drag fluctuations with $St = 0.47$ (based on the model height) was computationally obtained by Basara et al. [8]. Gilhome et al. [9] visualized large-scale hairpin vortex shedding at $St = 0.11$ behind the backlight of a production notchback car, and referred to shear-layer flapping. In their study, St was based on the reattachment length (~ 0.65 m) and was stated to match the frequency measured by Nouzawa et al. [7]. Shear-layer vortex shedding at a frequency approximately four times higher was also detected along the centerline. Strangfeld et al. [10] found no dominant frequencies from time-resolved surface pressure and force measurements, although shedding of large-scale vortices was

visualized using particle image velocimetry (PIV) in the near-wake region of the realistic generic car model “DrivAer” [11] with its fastback configuration.

The work by Sims-Williams et al. [12] is seemingly most relevant and informative to the present study. They experimentally revealed the existence of weakly coherent and periodic structures behind a realistic hatchback car model, involving not only symmetric oscillations (at $St = 0.3$ - 0.6 , based on the square root of the model frontal area) but also antisymmetric oscillations (at $St = 0.1$) between the two sides of the model. It is noteworthy that they implied the possible effect of the latter mode on the degraded straight line stability. More recently, Kohri et al. [13] confirmed the existence of such antisymmetric fluctuations of trailing vortices behind the generic fastback car model known as the Ahmed body [14] at around $St = 0.1$ (based on the square root of the frontal area), irrespective of the rear slant angle, although their main concern was the mechanism for the transition of the wake structure.

A primary goal of this study is to verify the hypothesis that fluctuations in the aerodynamic load (in particular, the lateral load) lead to a reduction in a vehicle's stability due to excitation of yawing (and rolling) vibrations, and that their suppression results in improved handling. An approach from the vertical viewpoint has been reported by Okada et al. [15], albeit in association with a change in rear ride height.

Large eddy simulations (LESs) were first conducted on hatchback car models under straight driving conditions in still air in order to identify the source of load fluctuations that could induce yawing (and rolling) vibrations. Wind-tunnel tests were then performed with the corresponding 28%-scale hatchback car models. Time-resolved loads and surface pressures were measured with an internal six-component balance and pressure transducers, respectively. The unsteady wake of the model was also investigated using hot-wire anemometry. The experimental results led to the concept of an effective device in terms of fluctuation reduction, whose effect on vehicle motion performance was subjectively evaluated on a track test with an actual hatchback car.

NUMERICAL AND EXPERIMENTAL METHODS

Hatchback Car Model

The subject for this study is a hatchback car model based on a production vehicle fitted with a rear roof spoiler, though the model details are quite simplified; for instance, it has a flat underfloor, no side mirrors, no under-hood/cooling air flow, simplified wheels, and so forth. Figure 1 shows the side, top, and rear views of the baseline hatchback model. The overall length L and the frontal projected area A of the car model are 4.226 m and 2.126 m², respectively. Also shown in Fig. 1 is the origin of the coordinate system used. Note that the positive x direction is downstream.

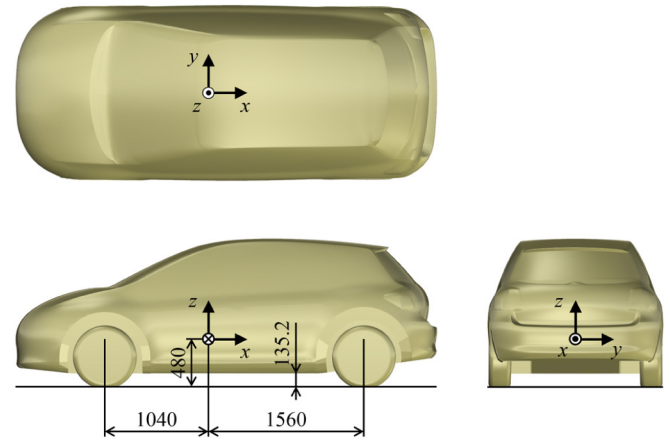


Figure 1. Baseline hatchback car model with all dimensions in millimeters and coordinate system used.

Large Eddy Simulation

Numerical simulations were conducted on the hatchback car model under straight driving conditions using an in-house LES code for three-dimensional incompressible flows. For the modeling of sub-grid scale (SGS) components, a mixed-time-scale SGS model was used, the advantage of which had already been established for several basic flows. A detailed description of the code is given in Ref. [16].

Figure 2 shows the computational domain employing an overlaid grid system, which consists of an inner structured grid and a background orthogonal grid. The inner grid surrounding the hatchback model is shown in Fig. 3. The number of inner grid points is 293 (L) $\times$ 179 (W) $\times$ 162 (H), and there are 80 $\times$ 69 $\times$ 45 points for the background grid. The minimum grid spacing is 1 mm; hence, an artificial wall boundary condition based on the three-layer wall function was applied to the wall surface.

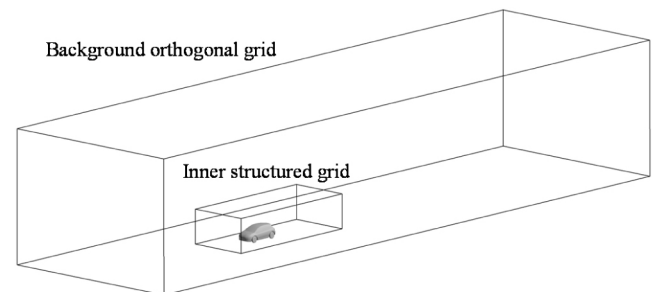


Figure 2. Computational domain employing an overlaid grid system.

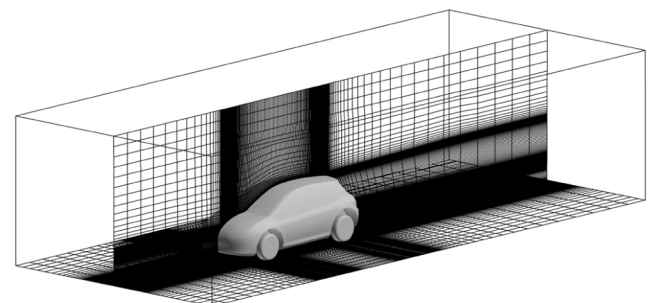
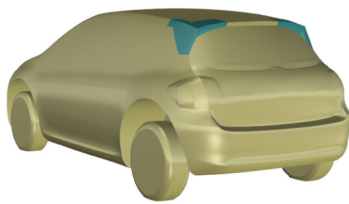


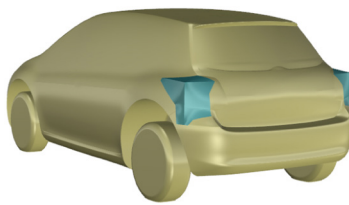
Figure 3. Inner structured grid surrounding the baseline model.

The free-stream velocity U_∞ was set to 33.3 m/s, which yields a Reynolds number of 9.38×10^6 based on the model length L . A velocity boundary condition equal to U_∞ was imposed on the ground plane, and wheel rotation was expressed in terms of the angular velocity boundary condition on their surfaces.

For the LES analysis, three configurations were considered: the baseline model and two modified models equipped with different aerodynamic devices, as depicted in Fig. 4. One is a “roof-side spoiler,” which is designed to extend the rear roof spoiler from its side end to the upper rear pillar; the other is a “combi-lamp spoiler,” which changes the shape around the rear combination lamp to provide a sharply angulated corner.



a. Roof-side spoiler configuration



b. Combi-lamp spoiler configuration

Figure 4. Modified hatchback car models for the LES analysis, with aerodynamic devices highlighted in blue.

The roof-side and combi-lamp spoilers were both originally expected to change the transient behavior for steering action. Although they received better subjective assessments compared with the baseline car, their effects could not be well explained by a preliminary vehicle motion analysis for a lane change maneuver, where the motion analysis was coupled with a transient aerodynamic load model derived for each configuration (for the detailed procedures, see Ref. [3], albeit this is for a vertical motion analysis). This load model was based on phase-averaged loads acquired in dynamic wind-tunnel tests for sinusoidal lateral motion, so the fluctuating components were inherently excluded in the motion analysis, even though the phase-averaged loads exhibited unique phase-shift behavior.

Scale-Model Wind-Tunnel Test

A wind-tunnel test was performed with the corresponding 28%-scale hatchback car model in a closed-circuit, 1/4-scale automotive wind tunnel at Toyota CRDL, Japan. The nozzle exit was 1.6 m in width and 1.2 m in height. The test section was 3/4 open and had a fixed floor. It should be noted that the ground conditions were not simulated in the same way as in the numerical simulations, although the test section floor was equipped with a boundary layer scoop and an air suction system. The maximum velocity was 42 m/s, and the turbulence intensity was less than 0.2% in the empty test section.

The car body was made of a carbon composite material and was supported from above by a vertical strut through a clearance hole in the body roof, as shown in Fig. 5. The stationary wheels were made of rigid polyurethane foam, and were fixed on the floor separately from the body. Although the influence of the overhead support strut on the flow field is non-negligible, as exemplified in Ref. [17], it is assumed to be insignificant for a relative comparison of the aerodynamic devices tested here.

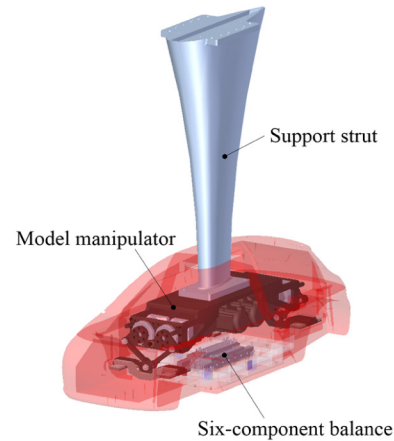


Figure 5. Wind-tunnel model supported by an overhead strut via a six-DOF model manipulator and a six-component balance.

The fluctuating pressure at selected points on the sides of the rear end was measured using miniature piezoresistive pressure transducers (Model 8507C-1, Endevco Corp.) with a full-scale range of 1 psi (= 6.895 kPa). The manufacturer quoted accuracy is 1.5% of the full-scale output. The pressure data were recorded at a sampling rate of 500 Hz using a signal conditioning system (Precision 28000, Precision Filters, Inc.) with a low-pass filter at 100 Hz. Each transducer was connected to a pressure tap inside the model via 25-mm-long stainless steel and silicone tubes with inner diameters of 1.1 mm and 1.5 mm, respectively. No phase or amplitude correction was performed.

The fluctuating aerodynamic forces and moments were measured using a compact six-component strain gauge balance mounted inside the model between the floor and a six-DOF model manipulator attached to the end of the support strut (see Fig. 5). The specifications for the balance are summarized in Table 1. The resonance frequencies in this load measurement system were found to be 11.7, 16.7, and 23.6 Hz for M_x , M_y , and M_z , respectively. The load data were sampled at 500 Hz using a strain amplifier (DPM-712B, Kyowa Electronic Instruments Co., Ltd.) with a low-pass filter at 100 Hz.

Table 1. Specifications of the six-component balance.

	F_x	F_y	F_z	M_x	M_y	M_z
Design load [N], [Nm]	120	120	120	30	60	60
Max. error [% FSO]	0.18	0.12	0.25	2.13	1.32	1.47

For the load measurements, two additional configurations were considered along with the aforementioned baseline, roof-side spoiler, and combi-lamp spoiler configurations. The “combined spoiler” configuration (not shown) is a simple combination of the roof-side and combi-lamp spoiler configurations. The “combi-lamp VG”

configuration features a delta-winglet vortex generator (VG) mounted on the rear combination lamp as depicted in Fig. 6. In the combi-lamp VG configuration, the delta VG was purposely aligned at a positive angle of attack α of 15° to ensure that a downforce, which is usually considered to be favorable, was not induced during the on-track test described later in this manuscript. Although the optimum α value was eventually confirmed to be around 15° in the examined range of -20 to 20° , it is reasonable to presume that the optimum angle depends on the oncoming flow angle, and hence, the results obtained in the absence of ground movement and wheel rotation are limited.

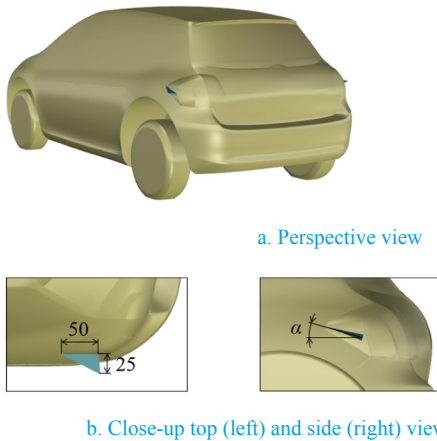


Figure 6. Modified hatchback car model for the wind-tunnel test, with a combi-lamp VG aerodynamic device highlighted in blue.

A wake survey was conducted for the selected configurations (the baseline and combi-lamp VG models). A constant-temperature anemometer (Model 1011, Kanomax Japan, Inc.) was used to measure the nominal streamwise velocity fluctuation behind the models using a tungsten single hot-wire probe with a horizontally aligned wire. The velocity signal through a linearizer (Model 1013, Kanomax Japan, Inc.) was low-pass filtered at 200 Hz and sampled at a rate of 800 Hz. During the hot-wire measurements, the load signal was simultaneously recorded to allow for cross-correlation analysis, and the sampling rate was set to be identical to that for the velocity signal.

The hot-wire probe was automatically traversed on a vertical (yz) plane perpendicular to the uniform flow at a position 21 mm downstream of the model, and on a horizontal (xy) plane located 250 mm above the test section floor. The locations at which the velocity fluctuation was measured are shown as black dots in Fig. 7. Note that the origin of the coordinate system is redefined here for simplicity such that $x = 0$ is at the rear bumper of the car body, and $z = 0$ is at the floor of the test section.

The free-stream velocity U_∞ was maintained at 40 m/s throughout the test, giving a Reynolds number of 3.15×10^6 based on the model length of 1.183 m.

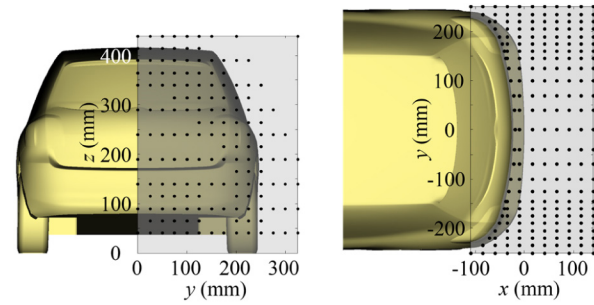


Figure 7. Locations of hot-wire measurements in the near-wake region (left: yz -plane 21 mm downstream of the hatchback car model; right: xy -plane 250 mm above the test section floor).

On-Track Subjective Evaluation

A subjective evaluation was made by four experienced drivers with the actual production vehicle from which the numerical and wind-tunnel car models were derived on a 5-km-long oval test track at the Toyota Motor Corp. Shibetsu Proving Ground. The vehicle speed was set to 120 km/h, which is equivalent to a flow velocity of 33.3 m/s in the LES analysis.

Based on the experimental and numerical results discussed later, two layouts for the delta VG(s) were chosen for comparison with the baseline car: the combi-lamp VG used in the wind-tunnel test and a “rear-pillar VG” with two delta VGs placed on each rear pillar. Figure 8 schematically illustrates the delta VG layout.

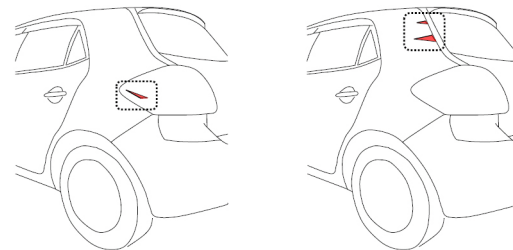


Figure 8. Schematic illustration of the delta VG layout (dotted lines) on the actual hatchback car for the on-track test (left: combi-lamp VG; right: rear-pillar VG).

The length and height of the delta VG in the on-track combi-lamp VG configuration are relatively small (140 mm and 50 mm, respectively) for the actual car, which is approximately 3.6 times the size of the scale model (for which they are 50 mm and 25 mm, respectively). The VG angle of attack of 15° is identical to that used in the wind-tunnel test. In the rear-pillar VG configuration, the lower VG has the same dimensions of 140×50 mm, the upper VG has dimensions of 70×25 mm, and the angle of attack is 10° for both.

RESULTS AND DISCUSSION

Large Eddy Simulation Results

Time-Averaged Flow Fields

Figure 9 shows distributions of the time-averaged static pressure coefficient (C_p) on the car model surface and the static pressure coefficient (C_{p_t}) on the yz -plane at a distance of $\sqrt{A}$ downstream of the