

Quantitative Representations of Aerodynamic Effects on Handling Response and Flat Ride of Vehicles

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ABSTRACT

The effects of aerodynamic coefficients on handling response and flat ride were quantified. For handling response, the aerodynamic effect was quantified by analysis with linear representation and a two-wheel simulation model, using aerodynamic coefficients obtained from a full scale car wind tunnel. The correlation of aerodynamic coefficients and handling response with driving feel was also ascertained. Aerodynamic yaw moment and side-force were also converted to equivalent front and rear lift to standardize aerodynamic indexes and improve aerodynamic development efficiency. For flat ride, steady and unsteady aerodynamic effects were quantified by analysis with a two-degree-of-freedom mass-spring-damper simulation model and aerodynamic coefficients obtained from a 35% scale model wind tunnel and towing tank test. Unsteady aerodynamic force occurrence mechanism was ascertained by unsteady CFD using dynamic mesh. This has made it possible to consider aerodynamic characteristics from the first stage of vehicle performance design.

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INTRODUCTION

In recent years, with the lightening of cars and adoption of low rolling resistance tires, aerodynamics have had a growing effect on smooth handling and ride comfort in vehicles. Aerodynamic coefficients and their sensitivities to vehicle attitude were already known to be a deciding factor in the vehicle performance, but there had been little quantitative demonstration of the relationship between the effects of each aerodynamic coefficient other than steady aerodynamic lift (henceforth CL) and other system characteristics in vehicles. A few studies have been conducted to investigate the effect of crosswind gusts has on unsteady aerodynamic yaw moment (henceforth CYM) and aerodynamic side force (henceforth CS) [1],[2],[3] and a few studies have been undertaken to determine targets for steady front and rear CL [4],[5],[6], but there were few indexes to determine targets for other steady and unsteady aerodynamic characteristics on handling response and flat ride in the early stage of vehicle performance design, when targets are set for system characteristics such as suspension. It has therefore not been possible to optimize vehicle performance by considering the effects that those aerodynamic characteristics and other system characteristics have on each other. This report quantifies the aerodynamic effect of the following two phenomena on vehicle performance, so that aerodynamic

characteristics can be taken into consideration in the early stages of vehicle performance design. First, this report demonstrates the effect that CYM and CS along with CL have on a vehicle's response to yaw direction during steering input. Second, it demonstrates the effect of the front and rear CL changes caused by changes in ride height and that of unsteady CL have on flat ride during road surface input.

For the first, handling response, analysis was first carried out to ascertain how yaw rate gain changed in relation to different aerodynamic specifications in vehicles on a two-wheel model. The analysis used aerodynamic coefficients obtained in a full scale car wind tunnel. Correlations between the results and driver feel were ascertained. Next, linear representation was used to show the relationship between CL, CYM, CS and cornering power (henceforth CP), and front and rear CL, CYM and CS were quantitatively converted to CP. At the same time, CYM and CS were converted to front and rear CL in a relational expression, giving an index called an equivalent CL map that could express aerodynamic characteristics using only a front and rear CL value including aerodynamic effects of CYM and CS. Establishing a relationship between aerodynamic coefficients and CP makes it possible to base vehicle performance design on aerodynamic characteristics, and the use of an equivalent CL map improves aerodynamic development efficiency. Finally,

correlations were established between the equivalent CL map and actual yaw rate gain measured against handling during test driving, to certify the aerodynamic effect on vehicle performance.

For the second, flat ride, analysis was carried out to determine the effect of different aerodynamic specifications on the vertical and pitching motions of the sprung mass on a two-degree-of-freedom mass-spring-damper simulation model. This analysis used front and rear CL sensitivity against ride heights obtained from a 35% scale model wind tunnel. Next, these changes of the sprung mass motions were converted into damping force to quantify the effect of steady CL ride height sensitivity on flat ride. Next, the unsteady front and rear CL during vehicle vibration was obtained accurately in slow motion by towing a basic 40% scale model vehicle in a towing tank while applying pitch and heave motion. These values were analyzed with a two-degree-of-freedom mass-spring-damper model to quantify the effect of unsteady CL on flat ride. Unsteady CL has been tested on simplified model vehicles such as Ahmed models [7],[8], but no such research has been done on models that closely resemble actual vehicles. There have also been no studies explaining the mutual effects of unsteady CL and ground effect by analyzing fluid phenomena around the vehicle. In the research for this report, unsteady CFD was carried out for the model using dynamic mesh. This made it possible to visualize the flow phenomena occurring around the vehicle and revealed the unsteady aerodynamic flow mechanisms occurring during vehicle vibration. Ascertaining the correlation with towing tank test results also ensured the accuracy of the unsteady CFD.

THE TWO-WHEEL MODEL AND TWO-DEGREE-OF-FREEDOM MASS-SPRING-DAMPER MODEL WITH AERODYNAMIC COEFFICIENTS

The two-wheel model used in the response analysis to steering inputs and the two-degree-of-freedom mass-spring-damper model used in the flat ride analysis both had aerodynamic features added using the following methods.

TWO-WHEEL MODEL

Figure 1 and Equations (1) and (2) show the two-wheel model used in this research. The tire model is a statistical model created in-house and simulated how tire CP changed according to changes in vertical load. For the aerodynamic forces affecting the vehicle, CYM and CS were directly input as external force, and front and rear CL was added to the tire model input as a change in the front and rear vertical load on the tires.

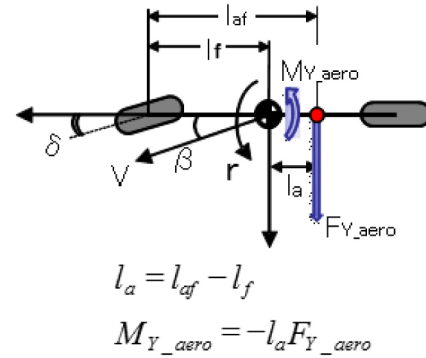


Figure 1. Two-wheel model

$$mV \left(\frac{d\beta}{dt} + \gamma \right) = -2K_f \beta_f - 2K_r \beta_r + \frac{\partial F_{Y_aero}}{\partial \beta} \beta \quad (1)$$

$$I_{zz} \frac{d\gamma}{dt} = -2K_f \beta_f l_f + 2K_r \beta_r l_r + \frac{\partial M_{Y_aero}}{\partial \beta} \beta \quad (2)$$

K is the tire CP obtained from the tire model.

$$K_f = T(m_f, F_{z_aero_f})$$

$$K_r = T(m_r, F_{z_aero_r})$$

(3)

NOMENCLATURE

m	Vehicle mass
V	Vehicle velocity
I_{zz}	Vehicle inertia on Z axis
β	Slip angle
γ	Yaw rate
l	Wheel base
F_{Y_aero}	Aero side force
M_{Y_aero}	Aero yaw moment
F_{Z_aero}	Lift
f	Front
r	Rear

TWO-DEGREE-OF-FREEDOM MASS-SPRING-DAMPER MODEL

Figure 2 shows the two-degree-of-freedom mass-spring-damper model used in this research. It has freedom of motion

in the heave and pitch directions. Equations (4) and (5) are motion equations showing motions of the sprung mass, with the addition of front and rear CL changes according to changes in ride height.

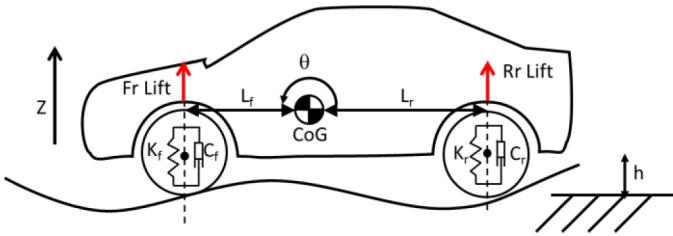


Figure 2. Two-degree-of-freedom mass-spring-damper model

$$m_b \ddot{z} = F_{sus_f} + F_{sus_r} + F_{z_aero_f} + F_{z_aero_r} \quad (4)$$

$$I_{yy} \ddot{\theta} = -l_f F_{sus_f} + l_r F_{sus_r} - l_f F_{z_aero_f} + l_r F_{z_aero_r} \quad (5)$$

Nomenclature

m_b	Sprung mass
I_{yy}	Sprung mass inertia on Y axis
z	Vehicle ride height
θ	Vehicle pitch angle
	Suspension is expressed as follows, with h as the input road surface change.

$$F_{sus_f} = 2k_f(l_f\theta - z + h) + 2c_f(l_f\dot{\theta} - \dot{z} + \dot{h})$$

$$F_{sus_r} = -2k_r(l_r\theta + z - h) - 2c_r(l_r\dot{\theta} + \dot{z} - \dot{h}) \quad (6)$$

Front and rear CL is calculated from CL ride height functions F and G obtained from the wind tunnel test, with ride height and pitch angle as variables.

$$F_{z_aero_f} = F(z, \theta, h)$$

$$F_{z_aero_r} = G(z, \theta, h) \quad (7)$$

EXPERIMENTAL AND CFD SETUP

For the purposes of this research, a full scale car wind tunnel experiment with no moving ground plane, a model wind tunnel experiment with moving ground plane, a towing tank experiment and unsteady dynamic mesh CFD were performed.

FULL SCALE CAR WIND TUNNEL

The aerodynamic coefficients used in the response analysis to steering inputs were obtained in the full scale car wind tunnel experiment shown in Fig. 3. Wind was supplied with circuit wind tunnel equipment. The equipment contained an open test section with a nozzle size of 28 m², and did not contain a moving ground plane. This meant that the changes in the vehicle's aerodynamic specifications came only from the upper surface of the vehicle, which was high off the ground.

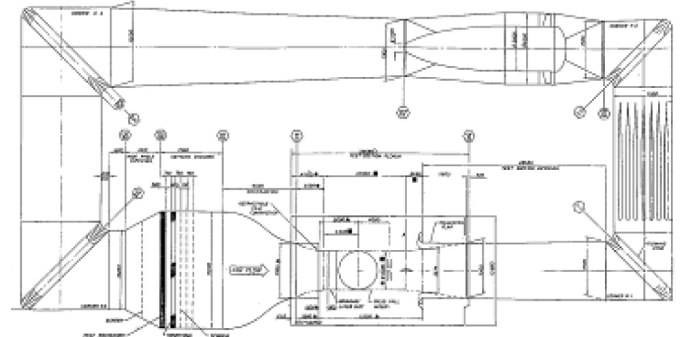
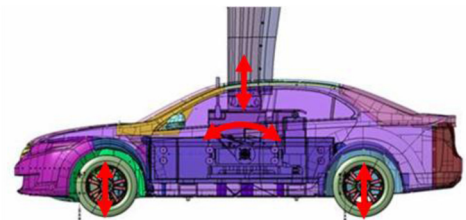


Figure 3. Overview of full scale car wind tunnel

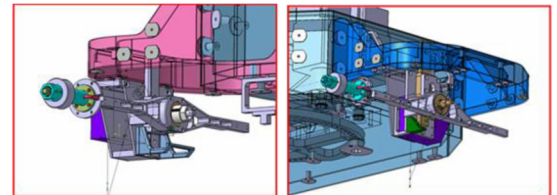
MODEL WIND TUNNEL AND 35% SCALE MODEL

To evaluate the effect of steady aerodynamics on flat ride in this study, a 35% scale model was put in a model wind tunnel with a moving ground plane to obtain ride height sensitivity figures for front and rear CL. Figures 4 and 5 shows the structure of the 35% scale model.



Pitch control: Weighed against interior
Ride height control: Vertical movement on a strut

Figure 4-1. Body of 35% scale model



Suspension structure: Center pivot method(No camber)

Figure 4-2. Suspension Structure of 35% scale model

Figure 4. Structure of 35% scale model



Figure 5-1. Shape of 35% model



Figure 5-2. Inner Structure of engine room



Figure 5-3. Underfloor Structure

Figure 5. Test conditions of 35% scale model

The pitch and heave were changed with struts and the aerodynamic forces were measured by internal balance. The suspension could move freely in a vertical direction and camber and tow did not change according to ride height. The shape of the vehicle was recreated faithfully, including engine room and underfloor structure. A perforated metal sheet was used for the radiator, with the same ratio of free stream velocity and air velocity through radiator core as an actual vehicle. The test wind speed was 45 m/s, and front and rear ride height was varied ± 10 mm from baseline ride height.

TOWING TANK TEST METHOD

Here is the test method used to evaluate the effect of unsteady CL on flat ride. Testing in water makes it possible to recreate fluid phenomena equivalent to those in air in slow motion, making it easy to correct the inertia that occurs from vibration of the model. It is also to recreate the vibration frequency of air with a lower vibration frequency, making it possible to recreate vehicle vibration accurately and take precise measurements of unsteady aerodynamics.

Test Conditions

The pitch and heave resonance frequency in an actual vehicle is around 1 Hz. A supposition was made that 1 Hz of resonance occurs in a vehicle travelling at 160 kph in air. In this case, the Strouhal number (St) is 0.11 as given by Equation (8).

$$St = \frac{l \cdot f}{V} \quad (8)$$

(f is the resonance frequency of the vehicle)

In the tank test, the Strouhal number is kept the same to recreate the unsteady aerodynamic phenomena as the above driving conditions. Due to limited towing distance in the tank test, the towing flow velocity is 3 m/s. In this case, the frequency applied to the 40% scale model tank used in this study is 0.2 Hz, given by Equation (9). The speed is 1/15 of actual driving conditions and the pitch frequency is 1/5, creating a slow-motion test environment.

$$f_{water} = \frac{V_{water} \cdot St}{l_{model}} \quad (9)$$

The Reynolds number (Re) in water is:

$$\begin{aligned} Re_{water} &= \frac{V_{water} \nu_{air}}{V_{air} \nu_{water}} Re_{air} \\ &= 0.37 Re_{air} \end{aligned} \quad (10)$$

(ν : dynamic coefficient of viscosity), around 40% of that in air. However, the fluid phenomena are not significantly different from the results for vehicle speed dependence in previous full scale car wind tunnel and scale model wind tunnel tests, making it a permissible value.

In this experiment, measurements were taken with pitch motion varied by ± 1 deg and frequency varied in 0.1 Hz increments from 0.1 Hz to 0.5 Hz.

Towing Tank Model

Figure 6 shows the 40% scale model, an overview of the towing tank and the test equipment. The scale model was a basic model with no mockup of the tires or engine room, but it was possible to recreate the longitudinal vortex generated on the A pillars and C pillars and pressure loss of back surface of the car. Shapes such as the pillars, under-floor, trunk and bumper can be replaced. The tank was 200 m long, 10m wide and 5 m deep. The towing equipment contained 6 force component load cells and held the 40% scale model upside down in the water. To limit rippling on the surface of the water, a ripple-proofing board 4.5m long and 1.8 m wide with a below-the-surface depth of 100 mm was attached. As the ripple-proofing board has a flat bottom, the ground effects

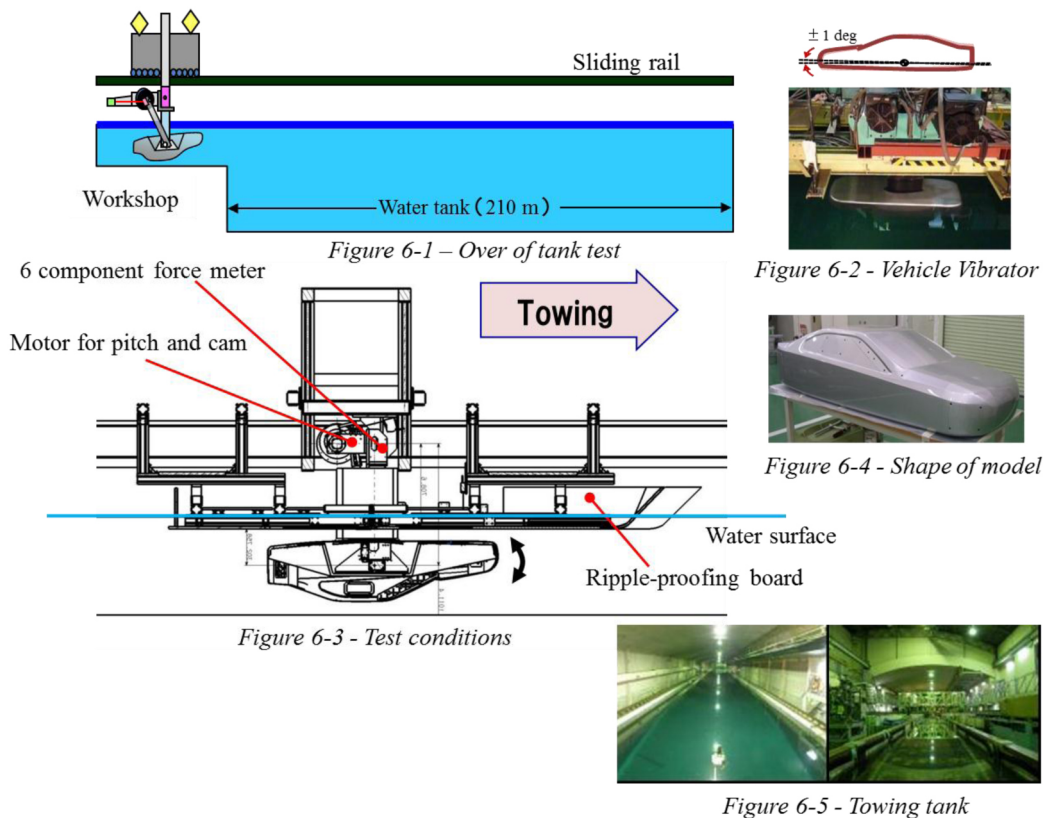


Figure 6. Overview of tank Test

that affect vehicles were simulated. The structural elements between the ripple-proofing board and the car body were covered with symmetric airfoil fairing. The jig to hold the model car was connected to the motor and cam at the base. The rotation of the cam made it possible to create a pitch motion from a sine wave with an amplitude value of 1 deg around a shaft installed near the model car's center of gravity. It was also possible to create a similar heave motion with an amplitude value of 10mm. To eliminate the inertia effect caused by the vibration of the model, the output data for vibration in air was subtracted from the output data for towing in water, with the resulting figures used as measurement data.

UNSTEADY DYNAMIC MESH CFD

Here is the unsteady CFD method with dynamic mesh used to ascertain the unsteady aerodynamic phenomena. As vibration has to be analyzed, the spring smoothing method and URANS were used as moving boundary methods. In the spring smoothing method, the edges connecting all of the node pairs in the mesh are considered spring interconnections. If change is applied to the boundary nodes, the change occurs across all of the springs connected to those nodes, and a force proportionate to that change occurs in all of the nodes. After all the spring forces achieve equilibrium, the nodes are updated to new positions.

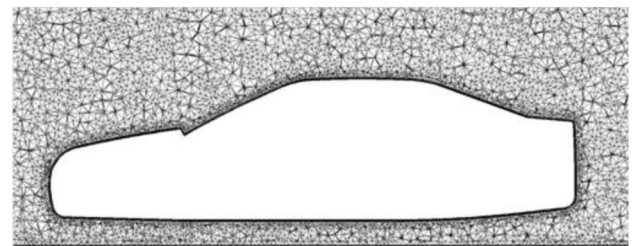


Figure 7-1. Mesh

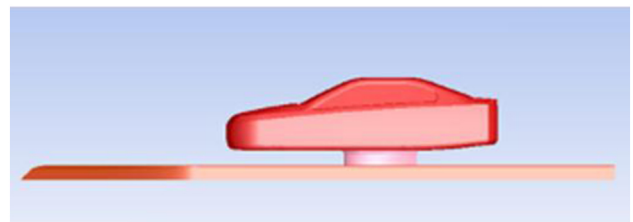


Figure 7-2. CFD model
Figure 7. CFD body model

For the analysis area, sectional surface YZ is the same as that used in the tank. For the target of analysis, a model was created with a surface mesh pitch of 4mm and an element count of around 20 million (Fig. 7). The turbulence model was a realizable k- ϵ with a time step of 0.01 seconds and a free stream velocity of 3 mps, equal to that of the tank test. The pitch angle and heave change were also the same as those used in the tank test: ± 1 deg and ± 10 mm. There were five vibrational frequency conditions, increasing in 0.1 Hz increments from 0.1 Hz to 0.5 Hz.

AERODYNAMIC EFFECT ON HANDLING RESPONSE

Figure 8 shows the front and rear CL for various aerodynamic specifications, obtained from the full scale car wind tunnel. As there was no moving ground plane in the full scale car wind tunnel, only aerodynamic specifications on the upper area of the body were varied, such as the rear spoiler or engine hood shape. Front and rear CL measurements were taken with the inflow yaw angle varied in 1 deg increments from 0 deg to 6 deg, to reflect actual crosswind conditions while driving. These CL figures were used in a frequency analysis on the two-wheel model to determine vehicle response to steering input varying from 0.005 Hz to 10 Hz. For the specifications of the two-wheel model, figures obtained from another K&C were used. Fig. 9 shows the steady yaw rate gain and yaw resonance frequency obtained for varying speeds.

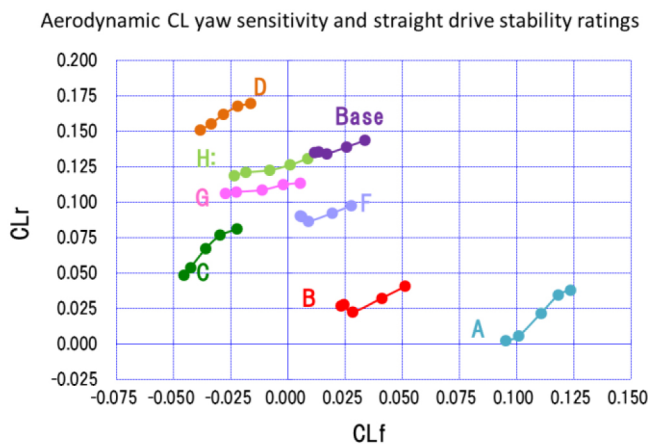


Figure 8. Front and rear CL for varying aerodynamic specifications in the full scale car wind tunnel

Differences in aerodynamic specifications become more marked as the speed increases. The graph also shows the drivers' feeling of stability while driving straight. © means "very good", ○ means "good", △ means "poor" and × means "very poor". The drivers were shown the wind-tunnel measurements for front and rear CL before test driving the vehicles, and told to rate the stability of the vehicle's response to steering it slightly (1Hz input) to the left and right while traveling at 180kph. For specification D, which had a high

rear CL, the car oversteered, making it unstable. Specifications A and B, with high front CL, were rated similarly poorly, with drivers commenting that the front tires did not feel firm on the ground. It is worth noting that while Specifications G and H (green circles on the graphs) and Specifications C and F (blue circles) had similar yaw rate gain and resonance frequency, they had a very different feel for the drivers.

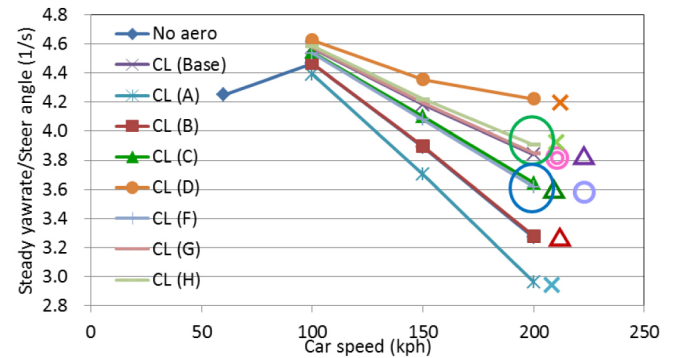


Figure 9-1. Steady yaw rate gain

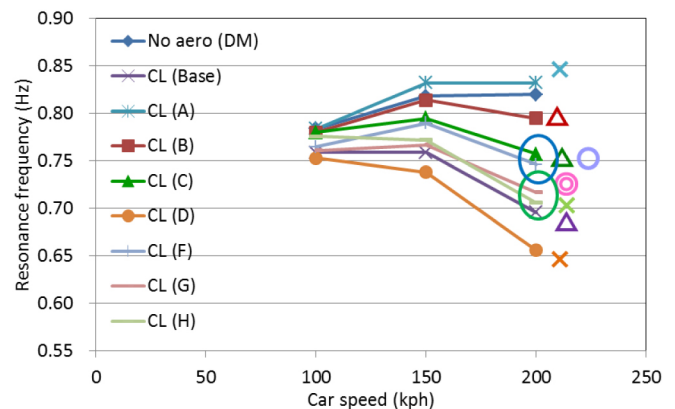


Figure 9-2. Yaw resonance frequency

Figure 9. Steady yaw rate gain and yaw resonance frequency with consideration given to CL

The front and rear CL obtained from the full scale car wind tunnel were insufficient for determining a correlation with driver feel. Further testing was therefore carried out to determine the correlation with driver feel using CS and CYM as well as front and rear CL. Figure 10 shows the CS and CYM values for inflow yaw angle in the full scale car wind tunnel.