

Crosswind Stability Simulation Technology for Performance Design in Model Base Development of Mass-production Vehicles

Takayuki TOYOSHIMA*

Yoshitomo AZEKATSU*

Naofumi IKEDA**

ABSTRACT

A simulation technology was developed that can be used in performance design with respect to crosswind stability for various vehicle types. This involves computation that takes the vehicle model used in the model base development of mass-production vehicles, and combines it with the model of driving conditions used to define actual vehicle tests for evaluation of crosswind stability. For the modeling of driving conditions, in particular, the time when the vehicle is entering the crosswind section and the time when the vehicle is exiting the crosswind section are treated separately, so both a continuous crosswind model, for a crosswind with continuously changing influence on the vehicle, and a discontinuous crosswind model, for discontinuously changing influence, were developed respectively. Combining these to define a half-continuous crosswind model enabled computation time to be shortened while still maintaining the necessary accuracy in calculations for performance evaluation of crosswind stability. The validity of this conceptual approach was verified using a 2014 model year FIT, and this simulation technology has enabled the study of specifications by means of crosswind stability simulation, for the development of other mass-production vehicles as well. The effectiveness of the technology was verified in development of the 2018 model year N-BOX.

1. Introduction

The development of automobiles has been growing increasingly complicated, and model base development (MBD) is an effective technique for efficiently advancing this kind of development. Figure 1 shows graphic representation of MBD as a V-model, where the central area enclosed by a red border shows the phases of performance design and performance verification (measurement). Performance design in MBD assumes that active use will be made of simulation. This necessitates a simulation environment that is capable of outputting computation results for a variety of performance design items within the limited time available in the development schedule. Therefore a simulation environment was developed with the capability of outputting results in a short enough time to enable actual use in chassis performance design for MBD of mass-production vehicles⁽¹⁾. The application of this simulation technology further enabled the examination of a number of performance design items that had not been

readily subject to examination in performance design for mass-production vehicle development up to that point. This technology can therefore be used for mass-production vehicle development. Simulation that predicts lap times⁽²⁾ is a typical example of such technology. In this paper, a

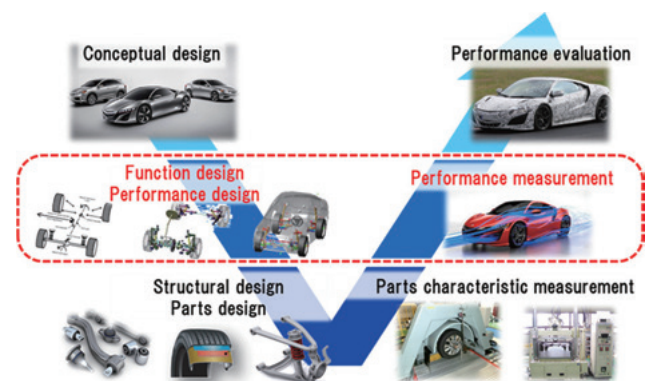


Fig. 1 V-Model

* Automobile R&D Center

** HRD Sakura

technique for simulation that predicts crosswind stability (hereafter referred to as crosswind stability simulation) will be described.

2. Evaluation of Crosswind Stability

Methods for testing crosswind stability in actual vehicles are prescribed in ISO 12021-1⁽³⁾. In conformance with that, JASO Z108⁽⁴⁾ also defines a test procedure for evaluating crosswind stability, and this testing method (hereafter referred to as the crosswind stability test) has shown results in performance evaluation during vehicle development. Mini-compact cars, tall minivans, and other such light-weight vehicles tend to be more influenced by crosswinds⁽⁵⁾, so it is particularly important to evaluate their performance using crosswind stability testing.

Figure 2 shows an overview of the crosswind stability test. For crosswind stability testing, first of all a crosswind blower is placed beside the test course to generate a crosswind on the course, creating a zone where a crosswind blows (hereafter referred to as the crosswind section). An actual vehicle is then driven through that crosswind section so that it moves across the crosswind at a specified speed, and the amount by which the line of the vehicle's path diverges laterally from a straight line due to the influence of the crosswind (hereafter referred to as the lateral displacement) is measured. The amounts of such lateral displacement are compared to evaluate crosswind stability. Figure 3 shows the yaw rate as an example of measurement data obtained from the crosswind stability test. Crosswind stability is evaluated using the lateral displacement determined from this kind of measurement data in combination with yaw rate peak values and changes in the yaw rate.

A crosswind stability test is a more elaborate procedure than other driving tests, so it requires more man-hours to carry out. It has been reasoned, therefore, that if a simulation could substitute for the crosswind stability test, then the examination of specifications could be performed

more efficiently, and various research efforts have been made up to now on simulation technology that predicts crosswind stability^{(6), (7)}. Most simulation technology developed to date, however, has been focused mainly on highly precise computation using complex models that attempt to accurately represent fine details of the vehicle shape as well as details of wind flow around such areas. Figure 4 shows a conceptual image of the computational model found in that type of simulation. That kind of simulation requires large amounts of data, in addition to which the model is complex. Consequently, it takes a long time to output the results, and such methods could not readily be applied to the development of mass-production

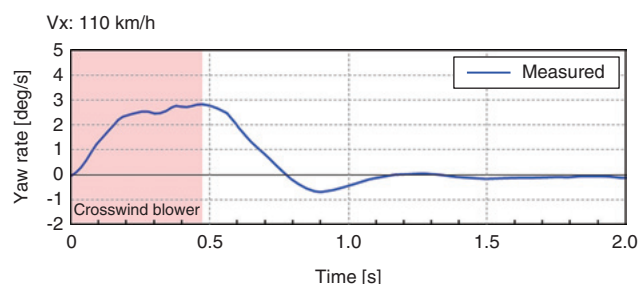


Fig. 3 Yaw rate in time series



Fig. 4 Crosswind simulation image

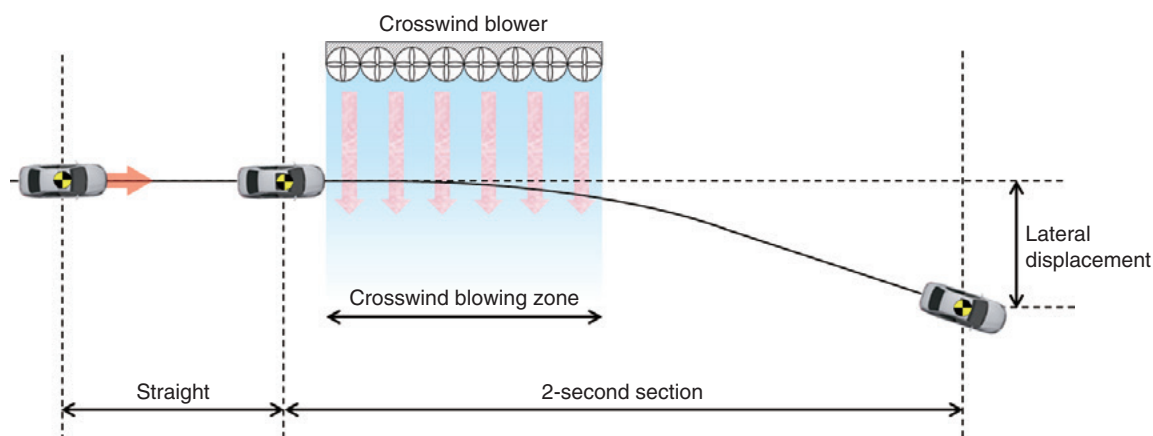


Fig. 2 Scheme of crosswind test

vehicles^{(8), (9)}.

If the simulation of crosswind stability could be performed using less data and a simpler model, then it could readily be included as an item for examination in all MBD performance design. Simulation that allows for computation using only the data acquired in the initial stages of development is particularly effective. Therefore it was decided to apply the vehicle model that had been created for the purpose of conducting MBD of mass-production vehicles.

3. Aims for the Developed Technology

The following three items were defined as the objectives for this technology, with the aim of developing a crosswind stability simulation method that would have sufficient accuracy to be effective in furthering performance design for MBD of mass-production vehicles.

- (1) Provides the ability to create a vehicle model using data that can be acquired in the initial stage of mass-production vehicle MBD.
- (2) Provides the capability to examine yaw rates and yaw rate peak values in addition to lateral displacement.
- (3) Provides the accuracy necessary for performance design in comparison with crosswind stability testing, and yields results within a time that allows for application to the development of mass-production vehicles.

4. Evaluation Indices

4.1. Crosswind Stability Test

The ISO and JASO standards for crosswind stability testing specify that the test vehicle should be driven at a speed of 100 km/h or 110 km/h. When developing mass-production vehicles, however, it is common to test across a broader range of vehicle speed conditions, starting at lower speeds and extending into higher speeds. Therefore the simulation should also be capable of a broader range of vehicle speeds.

The test specifications further call for crosswind at a velocity of 20 ± 3 m/s at the observation points in the crosswind section, for testing to be conducted in an environment with natural winds of 1 m/s or less, and so on^{(3), (4)}. The determination of crosswind stability is made from the lateral displacement of the center of gravity two seconds after the front end of the vehicle begins to enter the crosswind section. In mass-production vehicle development using actual vehicles, time series changes in the yaw rate, as observed in a two-second section and yaw rate peak values, are also referred to as evaluation indices.

The driving state of the vehicle when it enters the crosswind section greatly influences the accuracy of lateral displacement as an evaluation index for crosswind stability testing. This means that lateral displacement cannot readily be measured directly. Therefore, crosswind stability tests normally calculate lateral displacement from the yaw rates

generated in the two-second section, and use that calculated value as an evaluation index instead of direct measurement of lateral displacement. The JASO standard also takes the same conceptual approach to measurement of lateral displacement.

4.2. Method for Determining Lateral Displacement

Figure 5 shows the relationship of vehicle movement to a fixed X-Y coordinate system overlaid on the crosswind stability test course. The direction of straight ahead advancement that is the objective on entering the crosswind section is represented by the X-axis, and the direction of the wind that is blown onto the crosswind section is represented by the Y-axis. The X and Y axes are at right angles. The velocity of the vehicle is represented as V , with the velocity in the X-axis direction as V_x and the velocity of lateral displacement as V_y . The distance that the center of vehicle gravity moves in the direction of the Y-axis, two seconds after beginning to enter the crosswind section, is the lateral displacement that is the object of evaluation. The lateral displacement is determined by the value calculated using the measured yaw rate value r . If the yaw angle is θ , then θ is expressed by Eq. (1).

$$\theta = \int r \cdot dt \quad (1)$$

If the lateral acceleration is a_y and the body slip angle of the center of gravity is β , then β is expressed by Eq. (2).

$$\beta = \int \left(\frac{a_y}{V} - r \right) \cdot dt \quad (2)$$

From this, the displacement Y_i in the Y direction on the coordinate system that is fixed on the ground can be determined using Eq. (3).

$$Y_i = V \int [\sin(\theta + \beta)] dt \quad (3)$$

However, the value of β is normally lesser than θ , enough so that if the yaw rate can be correctly determined in the two-second section, then the lateral displacement can also be determined with sufficient accuracy.

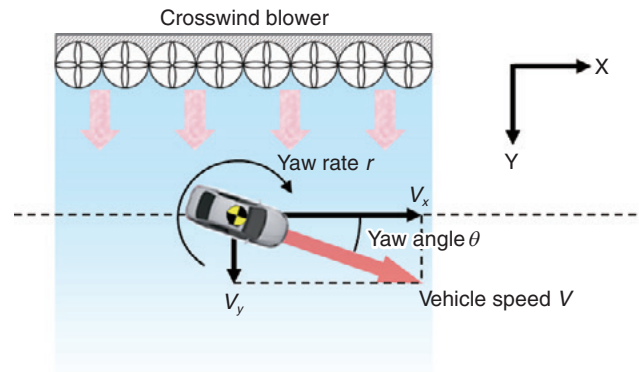


Fig. 5 Crosswind simulation

5. Simulation Model

5.1. Computational Model of Vehicle Conditions

The vehicle conditions dealt with here are the vehicle dimension specifications, component characteristics, and other such elements related to the dynamic performance of the vehicle. Specifically, these are the vehicle mass, the moment of inertia, the wheelbase, the center of gravity, the front and rear tire characteristics, the front and rear suspension characteristics, and the aerodynamic characteristics of the vehicle. The vehicle data used in MBD of mass-production vehicles can be used for these items of data on characteristics. The vehicle data used in MBD of mass-production vehicles has been described in a previous report⁽¹⁾.

5.2. Computational Model of Driving Conditions

There is a method that allows convenient computation of the influence of a crosswind by supposing that the force applied to the vehicle when passing through the crosswind section is a constant force that is generated as a rectangular wave for a set period of time. Here the computational model for this method is referred to as the discontinuous crosswind model. Figure 6 shows an overview of the discontinuous crosswind model. Some characteristics of the discontinuous crosswind model are that the vehicle mass is represented by mass points and that transient changes in aerodynamic characteristics that occur during entry and exit are not taken into consideration. As the result of a constant crosswind being applied to the aerodynamic center of a vehicle with a specific aspect, a yaw moment is generated around the center of gravity, with the distance from the aerodynamic center to the center of gravity of the vehicle as the moment arm length. A yaw moment is generated from the change in yaw angle that occurs between the instant when the leading edge of the vehicle enters the crosswind section and the instant when the leading edge of the vehicle exits the crosswind section. The magnitude of the yaw moment is largely determined by the force of the crosswind working

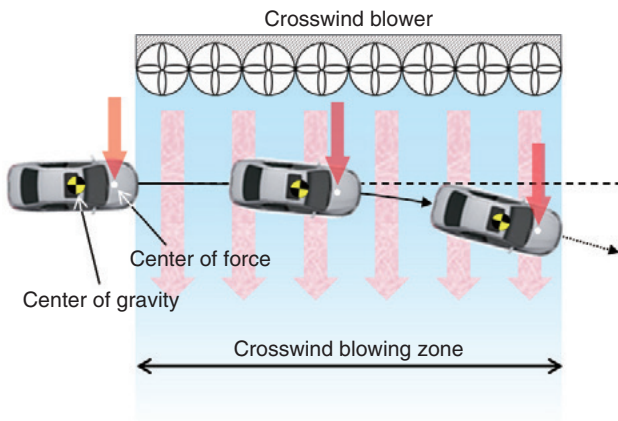


Fig. 6 Discontinuous crosswind model

Table 1 Specification list (FIT)

	FIT
Length × Width × Height [m]	3.990 × 1.695 × 1.525
Wheelbase [m]	2.530
Track Front/Rear [m]	1.480/1.470
Weight [kg]	1080

on the vehicle body according to the yaw angle change and the distance from the aerodynamic center to the center of gravity of the vehicle. Figure 7 shows a graph depicting the change in yaw moment generated in the vehicle body during passage through the crosswind section. In the discontinuous crosswind model, there is discontinuity between the yaw moments while driving through the crosswind section and while driving outside the crosswind section. Since this computational model is simple, it does not need large amounts of data to create a model. This also has the advantage that the computational burden is smaller, so that results can be output in a shorter time.

Regarding the 2014 model year FIT (hereafter FIT), Fig. 8 shows a graph that compares the computation results for yaw rate using the discontinuous crosswind model with the yaw rate measured in an actual crosswind stability test. The main specifications of the FIT are as shown in Table 1.

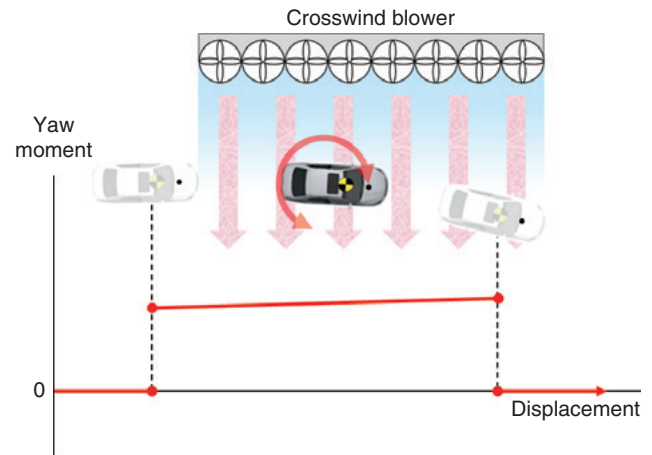


Fig. 7 Yaw moment of discontinuous crosswind model

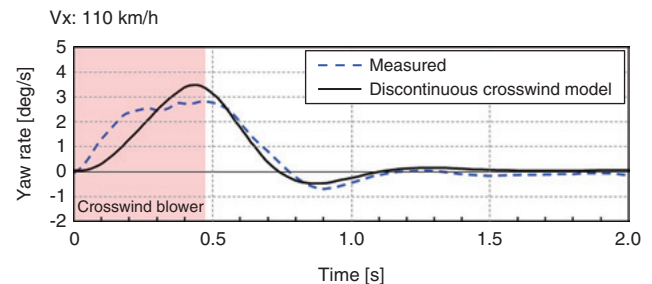


Fig. 8 Comparison of yaw rate in time series

The horizontal axis in Fig. 8 is the time, with the instant of entry into the crosswind section as zero seconds. The computation and measurement condition for both is 110 km/h. It can be confirmed from this graph that a peak occurs in the computation results for crosswind stability simulation after around 0.4 to 0.5 seconds, and that the results converge after around 1.5 seconds. By contrast, the results of the crosswind stability test using an actual vehicle show the yaw rate starting to rise at an earlier stage, with the first peak appearing after about 0.2 seconds, and the last peak occurring after about 0.5 seconds, and the results converging after around 1.5 seconds. The computation results from the discontinuous crosswind model and the measurement results from the crosswind stability test differ in how the yaw rate manifests, in the location of the yaw rate peaks, and so on, so that the computation results for lateral displacement produced from the simulation differ from those from the test results.

The continuous crosswind model sought a means for computing the rise in the yaw rate immediately after entry into the crosswind section and the first peak that occurs in the yaw rate by considering to make continuous changes in the yaw moment in accordance with the total length of the vehicle before and after entering the crosswind section, and before and after exiting the crosswind section. Figure 9 shows an overview of this approach. In the continuous crosswind model, the yaw moment is defined by dividing the passage through the crosswind section into three phases: (a) the phase of entry to the crosswind section, (b) the phase of passage through the crosswind section, and (c) the phase of exit from the crosswind section.

Figure 10 depicts the magnitude of the yaw moment generated in the vehicle body as computed by the continuous crosswind model. In the continuous crosswind model, the vehicle body is subjected to the crosswind while passing through the crosswind section, and the yaw moment that is thereby generated is continuous with the yaw moment (which is zero) generated while driving outside the crosswind section. This yaw moment changes transiently with the passage section, which corresponds to

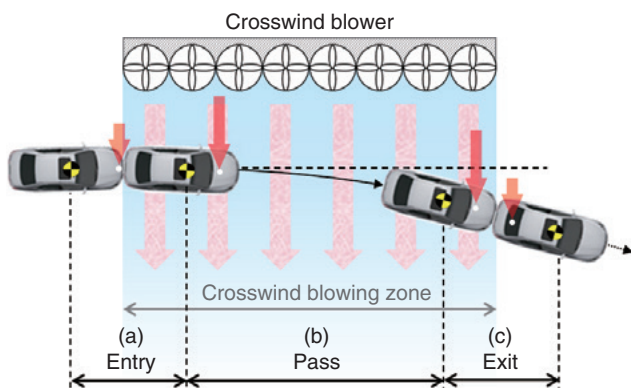


Fig. 9 Continuous crosswind model

the total length of the vehicle. Figure 11 shows the yaw rate computation results from the continuous crosswind model plotted onto the graph in Fig. 8. It is apparent from this graph that the results from the crosswind stability test and the computation results from the discontinuous model yield yaw rates that match closely from entry into the crosswind section to around 0.5 seconds after entry. However, it is also apparent that the calculated value and measured value diverge to a large extent from 0.5 seconds after exit from the crosswind section to around 1.0 second after exit.

Therefore a new model was devised in which the continuous model is used for the first half of passage through the crosswind section, where the yaw moment changes transiently, and the discontinuous model is used for the yaw moment in the last half. This has been designated the half-continuous crosswind model. In the half-continuous crosswind model, the yaw moment is taken to become zero when the vehicle reaches the exit of the crosswind section.

Figure 12 depicts the magnitude of the yaw moment that is generated in the vehicle body computed by the half-continuous crosswind model. Figure 13 shows a graph with the computation results from the half-continuous crosswind model plotted onto Fig. 11. It can be confirmed from this graph that the computation results from the half-continuous crosswind model match closely with the measurement results from the crosswind stability test. Of the three, the

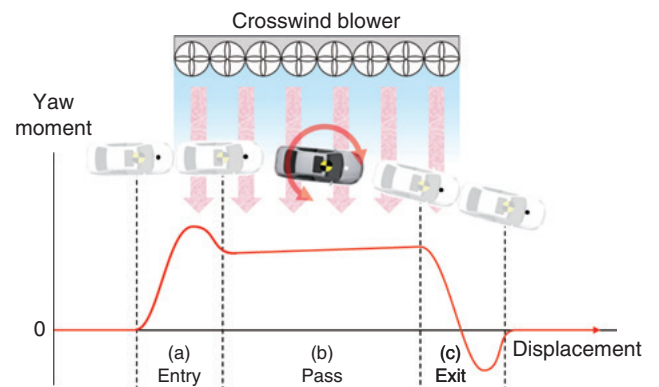


Fig. 10 Yaw moment of continuous crosswind model

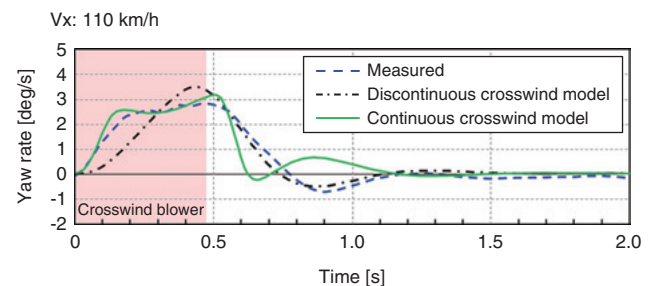


Fig. 11 Comparison of yaw rate in time series

half-continuous crosswind model tends to produce the closest results to the crosswind stability test. Figure 14 shows a bar graph presenting the measurement results for lateral displacement, which is the evaluation index for the

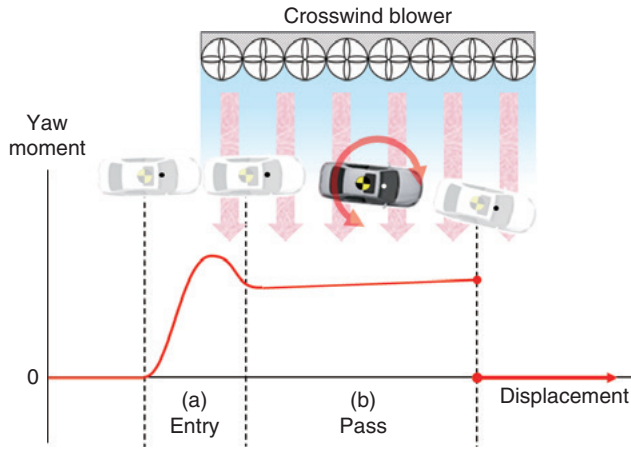


Fig. 12 Yaw moment of half-continuous crosswind model

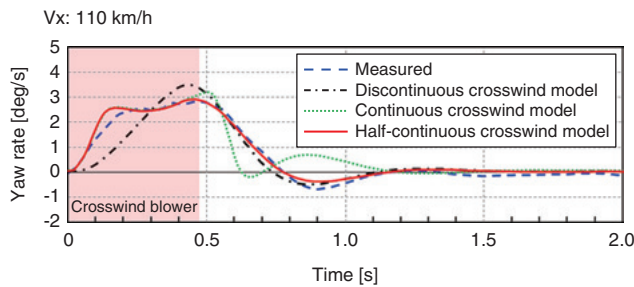


Fig. 13 Comparison of yaw rate in time series at 110 km/h

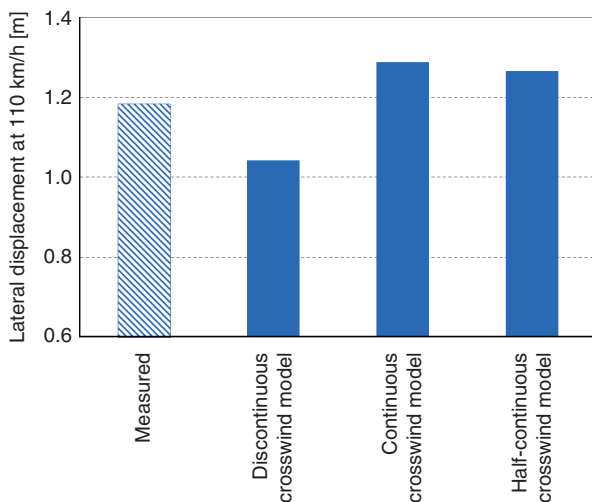


Fig. 14 Comparison of lateral displacement at 110 km/h

crosswind stability test, compared with the computation results for lateral displacement determined from the discontinuous crosswind model, the continuous crosswind model, and the half-continuous crosswind model. These computation results show that use of the half-continuous crosswind model yields simulation results for crosswind stability with an accuracy that makes this model effective for performance design.

5.3. Verification of the Half-continuous Crosswind Model

A graph that compares the computation results from the discontinuous crosswind model, the continuous crosswind model, and the half-continuous crosswind model with the measurement results from crosswind stability testing, where the vehicle speed condition has been changed to 140 km/h, is shown in Fig. 15. A similar graph that compares lateral displacement is shown in Fig. 16. It is apparent from these computation results that even when the speed condition is changed, the half-continuous crosswind model yields results that match closely with those from the crosswind

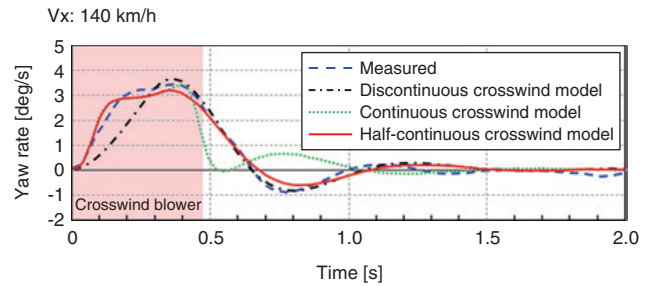


Fig. 15 Comparison of yaw rate in time series at 140 km/h

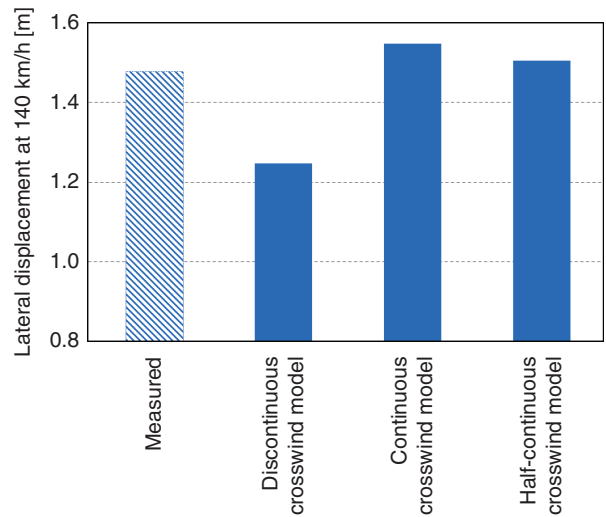


Fig. 16 Comparison of lateral displacement at 140 km/h

stability test.

As for the crosswind stability test, there have been reports to date on research regarding the conceptual approach to the entry portion of the crosswind section^{(10), (11)}. There were few examples, however, that discussed the conceptual approach to the exit portion of the crosswind section. There have been only a few examples in the past of simulation models that are like the half-continuous crosswind model devised in the current research in grasping the whole, made up of the entry portion to the crosswind section together with the exit portion from the crosswind section. The half-continuous crosswind model is a new simulation model that has been proposed in order to achieve a balance between accuracy in computation of crosswind stability and computation time.

6. Cases of Application of Simulations

The previous chapter discussed the crosswind stability simulation technology that was created through development of the FIT. Next, the effectiveness of this approach in similar application to the development of other mass-production vehicles was confirmed. The following is a case of application of the developed simulation technology to development of the 2018 model year N-BOX (hereafter referred to as the new N-BOX).

Table 2 shows the main specifications for the new N-BOX. Since the N-BOX had a body shape that made it susceptible to the influence of crosswinds, there was a need to examine specifications that would also realize other aspects of performance without degrading crosswind stability. It is particularly important in this case to seek as high a level of crosswind stability as could be managed from the initial stages of development. Given this context, the developed simulation technology was utilized for the new N-BOX as it had been for the FIT.

Figure 17 shows the study results from examination conducted during development of the new N-BOX. These results can be used in confirming the effectiveness of measures taken with regard to lateral displacement and yaw rate peak value. This kind of study enables simultaneous consideration of other performance elements as well as the discovery of effective measures to implement for them.

Figure 18 presents a graph showing the effectiveness of measures actually taken in various chassis components during development of the new N-BOX. This approach is effective for system design that advances the examination of specifications while taking into account the influence of the various chassis components on crosswind stability, and that ultimately finds the specifications that are able to achieve the objectives. In the present case of the new N-BOX, the objectives were achieved in terms of reduction in weight and design constraints by weight distribution, tire characteristics, suspension characteristics, aerodynamic characteristics, and other such factors. This indicated that

Table 2 Specification list (N-BOX)

	N-BOX
Length × Width × Height [m]	3.395 × 1.475 × 1.790
Wheelbase [m]	2.520
Track Front/Rear [m]	1.305/1.305
Weight [kg]	890

the developed simulation technology is able to allocate crosswind stability performance to each of the components at the stage of performance design for MBD of mass-production vehicles.

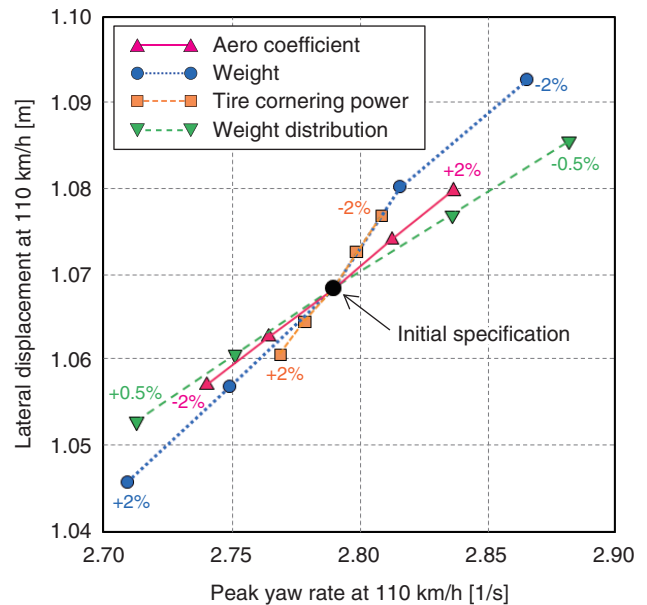


Fig. 17 Peak yaw rate and lateral displacement

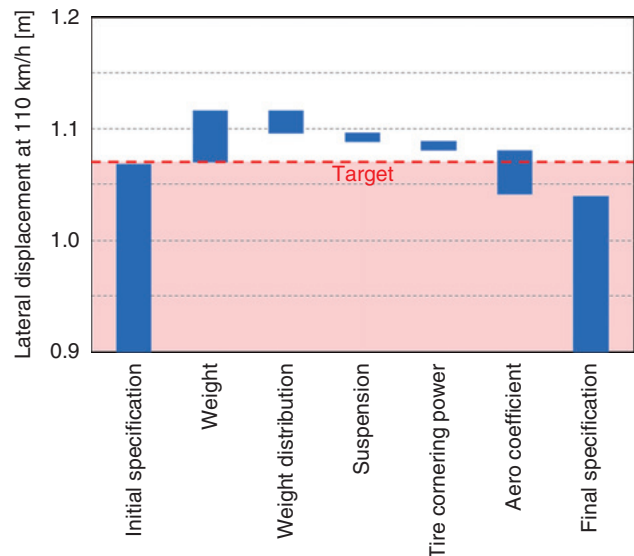


Fig. 18 Lateral displacement (N-BOX)

Figure 19 is a graph showing the extent to which the final specifications are dependent on vehicle speed where crosswind stability is concerned, as verified with an actual vehicle. Values below the criteria prescribed in standards were achieved in the interval between the two points of 80 km/h and 110 km/h, and the specifications for crosswind stability were determined accordingly. It was apparent that the developed simulation technology was useful in the development of a mass-production vehicle.

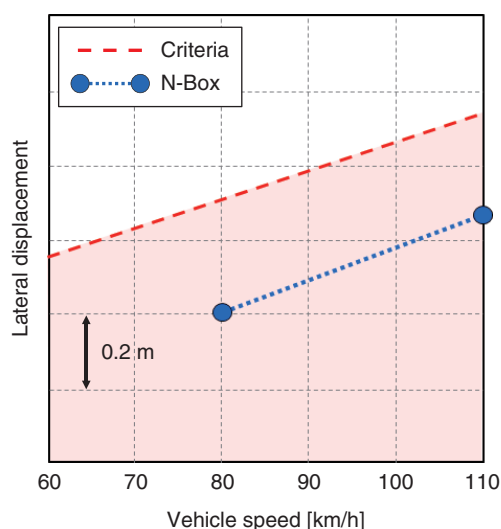


Fig. 19 Lateral displacement (N-BOX)

7. Conclusion

The developed simulation technology has enabled examination of specifications that include crosswind stability for performance design in MBD of mass-production vehicles.

- (1) A simulation technology was developed that can compute predicted crosswind stability utilizing the vehicle data used in MBD of mass-production vehicles.
- (2) The developed simulation method can yield computation results that are close to measurement values not only for lateral displacement, but also for yaw rate and yaw rate peaks.
- (3) It was verified that use of the half-continuous crosswind model could also enable the application of performance design for crosswind stability to the development of mass-production vehicles, in terms of computation time and computation accuracy.

References

- (1) Toyoshima, T., Matsuzawa, T., Ito, K., Endo, Y., Takano, H., Ushimura, T.: Development of Chassis Performance Design Technologies for MBD of Mass-production Vehicles, Honda R&D Technical Review,

Vol. 29, No. 1, p. 52-62

- (2) Toyoshima, T., Matsuzawa, T., Ushimura, T.: Lap Time Simulation Technology for Performance Design during Production Car Development, Honda R&D Technical Review, Vol. 29, No. 2, p. 124-133
- (3) ISO 12021-1: Road vehicles - Sensitivity to lateral wind - Open-loop test method using wind generator input, (2010)
- (4) JASO Z108: 2004, Road vehicles - Test procedure of lateral wind stability (in Japanese)
- (5) Takada, H., Nakagawa, K., Shinoda, H.: Crosswind Stability of 1-box Car, Journal of Society of Automotive Engineers of Japan, Vol. 43, No. 3, p. 119-126, (1989) (in Japanese)
- (6) Kobayashi, T., Kitoh, K., Saga, T., Hirukawa, M.: A study on an automotive vehicle in crosswind, 1st Report, Seisan Kenkyu, Vol. 30, No. 7, p. 278-281, (1978) (in Japanese)
- (7) Maruyama, Y., Yamazaki, F.: NUMERICAL ANALYSIS AND DRIVING SIMULATOR EXPERIMENT ON THE STABILITY OF A VEHICLE UNDER STRONG CROSS-WIND, Proceedings of JSCE, No. 766, I-68, p. 129-140, (2004) (in Japanese)
- (8) Nakasato, K., Takase, H., Kiyono, M., Kouno, K., Ishihara, Y., Shiozawa, H.: Prediction of Aerodynamics Effect on Vehicle Motion under Transient Crosswind Condition, using by Coupling Simulation of CFD (Computational Fluid Dynamics) and MBD (Multi Body Dynamics), JSAE Annual Congress Proceedings, No. 25-14, p. 1-4, (2014) (in Japanese)
- (9) URL: <http://www.aics.riken.jp/shirutsudo/meeting9.html>
- (10) Kuroda, S., Tanaka, S., Ueno, K., Tanaka, H.: Development of aerodynamic transient force measurement running into crosswind, JSAE Annual Congress Proceedings, No. 21-13, p. 1-4, (2013) (in Japanese)
- (11) Ryan, A., Dominy, R. G.: The Aerodynamic Forces Induced on a Passenger Vehicle in Response to a Transient Cross-Wind Gust at a Relative Incidence of 30°, SAE Technical Paper 980392, p. 1-4, (1998)

■ Author ■



Takayuki TOYOSHIMA



Yoshitomo AZEKATSU



Naofumi IKEDA