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Driving simulator experiment on the moving stability of an automobile under strong crosswind

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Abstract

In expanding expressway networks in Japan, various types of structures have been constructed, e.g., long span bridges and bridges with high piers. The expressway structures are well designed for the external dynamic forces, e.g., earthquakes and strong winds. However, for further safety promotion of the expressway networks, it is important to evaluate the drivers' responses under strong dynamic disturbances. The present authors have investigated the moving stability of a vehicle under seismic motion based on both numerical simulation and virtual experiments using a driving simulator. Strong crosswind is considered as another factor that makes it difficult for drivers to control their vehicles. This study investigates the moving stability of a vehicle under strong crosswind based on numerical analyses and driving simulator experiments. To predict the future position of a moving vehicle including the reaction of a driver, the second-order predictable correction model is used in the numerical analyses. The results obtained from the numerical and experimental studies are compared and the validity of the driver model is discussed. It is expected that this research is helpful for the decision-making of expressway closure under strong wind and the design of wind barriers.

Keywords: Driving simulator; Expressway; Strong crosswind; Driver–vehicle interaction

1. Introduction

The present authors have performed a series of virtual tests using a driving simulator to investigate the characteristics of drivers' responses during strong seismic shaking [1]. The

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driving simulator, which was developed by Mitsubishi Precision Co. Ltd, displays a scenario highway course on three large screens with LCD projectors, and also provides the sound of a real car. This driving simulator has six servomotor-powered electric actuators, which can simulate six components of motion of a vehicle: three translational and three rotational components [2].

As an important factor that affects safety driving on expressways, strong crosswind should be taken into consideration [3]. Japan Highway Public Corporation (JH) owns expressway networks of over 8200 km throughout Japan. In expanding expressway networks, various types of structures have been constructed, e.g., long span bridges and bridges with high piers. Vehicles in the immediate wake of bridge towers sometimes suffer from difficult controllability [4,5]. Large-sized vehicles are sometimes overturned because of strong crosswind [6]. In addition, drivers find it difficult to control their vehicles when the wind speed changes abruptly, e.g., when they are at the exit of a tunnel, at the wind path in a valley, at a gap of wind barriers and so on. JH closes the expressways when the average wind speed for 10 min is $\geqslant 25$ m/s in an ordinal case. However, this regulation level is determined empirically. In fact, if the average wind speed for 10 min becomes >15 m/s, highway police and JH will judge whether to open or to close the expressway after trials of driving.

In this study, the moving stability of a vehicle subjected to strong crosswind is investigated using both numerical simulation and driving simulator experiments. In addition, the validity of a numerical model considering the driver–vehicle interaction is discussed based on the driving simulator experiments.

2. Modeling of moving vehicle responses under strong crosswind and its responses without considering driver's reactions

Fig. 1 shows the coordinate of a vehicle model employed in this study. This vehicle model has a six-degree-of-freedom system, but the bouncing motion (vertical motion) is not calculated because undulation of road surface is not considered in this study. The vehicle is modeled as a mass-spring system and the equations of motion of a moving

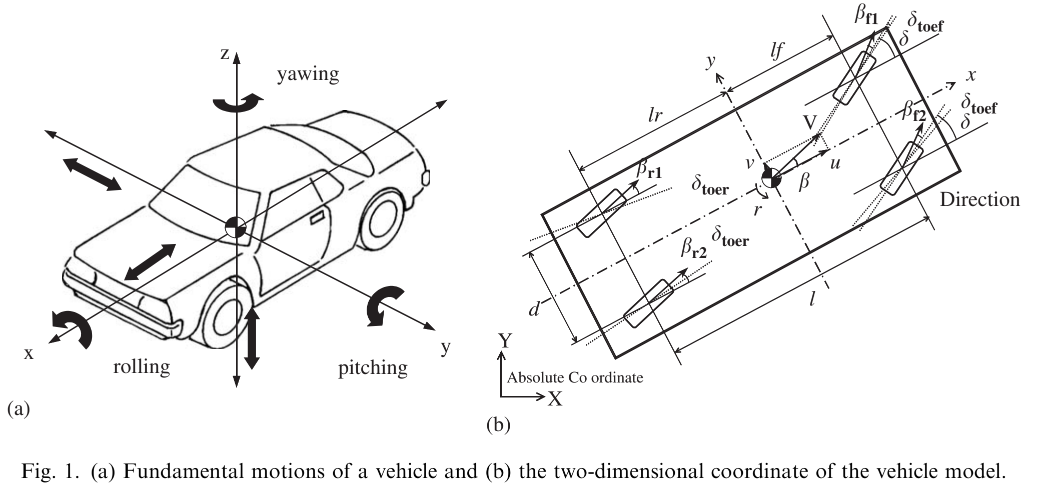

Fig. 1. (a) Fundamental motions of a vehicle and (b) the two-dimensional coordinate of the vehicle model.

vehicle [7] are described as

$$m(\dot{u} - v\dot{\psi}) = \sum_i \sum_j (F_{xij} \cos \delta_{tij} - F_{yij} \sin \delta_{tij}) = \sum_{i,j} F'_{xij}, \tag{1}$$

$$m(\dot{v} + u\dot{\psi}) = \sum_i \sum_j (F_{xij} \sin \delta_{tij} + F_{yij} \cos \delta_{tij}) = \sum_{i,j} F'_{yij}, \tag{2}$$

$$I_z\ddot{\psi} = (F'_{y11} + F'_{y12})l_f - (F'_{y21} + F'_{y22})l_r + (-F'_{x11} + F'_{x12})\frac{d}{2} + (-F'_{x21} + F'_{x22})\frac{d}{2}, \tag{3}$$

where u and v are the vehicle velocities in the longitudinal and transverse directions, respectively, ψ is the yaw angle, and δ_t the angle difference between the longitudinal direction and the direction of each front tire. F_x and F_y are the longitudinal and transverse forces acting on each tire, respectively, which are obtained using the Magic Formula Model [8]. The subscript i represents the front or rear wheel and the subscript j represents the left or right wheel. I_z is the mass moment of inertia of the vehicle about the vertical direction. l_f and l_r are the distances between the center of gravity (c.g.) and the front wheel and that between the c.g. and the rear wheel, respectively, and d is the distance between the right and left wheels. The rolling and pitching motions are obtained through the same algorithms using the same parameter values in our previous study [9].

As shown in Fig. 2, the vehicle is assumed to be subjected to the uniform crosswind. The lateral force, Y_w, and yawing moment, N_w, applied to the moving vehicle are obtained as

$$Y_w = C_y \rho S\{u^2 + (v + w)^2\}/2, \tag{4}$$

$$N_w = C_n \rho S(l_f + l_r)\{u^2 + (v + w)^2\}/2, \tag{5}$$

where S is the front area of the vehicle, ρ the density of air, and w the wind speed applied to the vehicle. C_y and C_n are the aerodynamic coefficients for the lateral force and yawing moment, respectively, which are the functions of the aerodynamic slip angle, β_w $(= \arctan\{(v + w)/u\})$. In this study, these coefficients were set to be the same as those

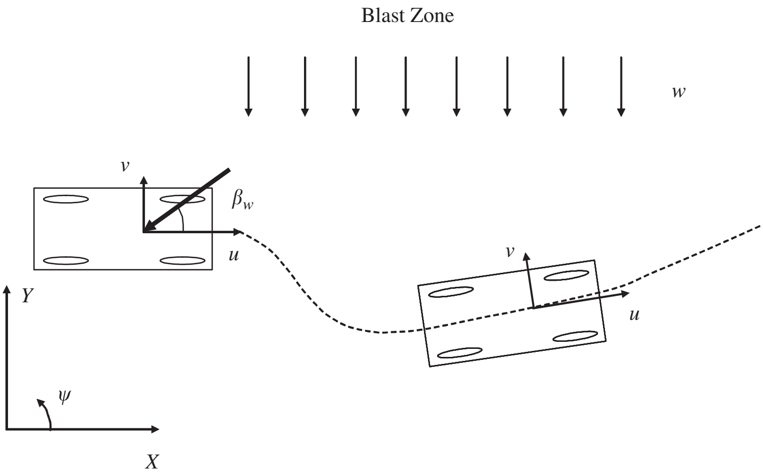

Fig. 2. Vehicle model and crosswind disturbance.

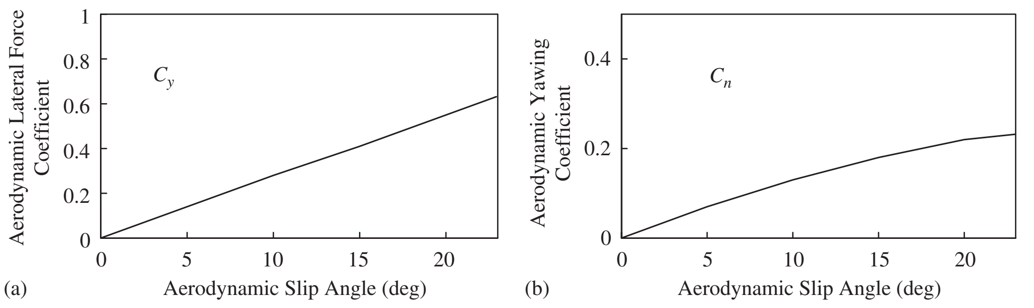

Fig. 3. Aerodynamic coefficients for (a) the lateral force and (b) the yawing moment used in this study.

Table 1
Parameters of the vehicle model used in this study

Parameters	Definition	Value	Unit
m	Mass of the vehicle body	1100	kg
l_f	The length between the center of gravity and the front wheel	1.0	m
l_r	The length between the center of gravity and the rear wheel	1.635	m
I_z	Inertial moment for yawing motion	637	kg m^2
d	The length between right and left wheels	1.505	m
ρ	The density of air	1.245	kg/m^3
S	The front area of the vehicle	1.92	m^2

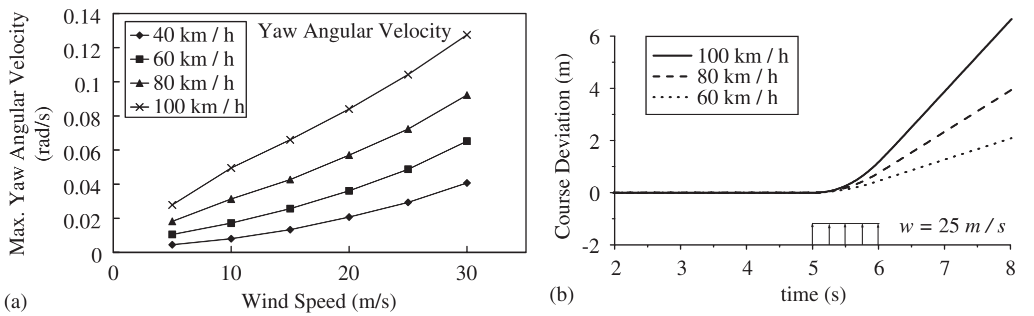

Fig. 4. (a) Relationship between the maximum yaw angular velocity of the moving vehicle and the wind velocity and (b) lateral displacement of the moving vehicle without considering the driver's reaction. The wind speed is 25 m/s.

used in the vehicle model programmed in the driving simulator, which models a compact car [10] (Fig. 3).

Substituting the aerodynamic forces obtained from Eqs. (4) and (5) to the equations of motion of a vehicle (Eqs. (2) and (3)), numerical simulation of the moving vehicle subjected to crosswind without considering driver's reactions can be conducted. Table 1 shows the parameters of the vehicle model employed in this study.

Fig. 4(a) shows the relationship between the maximum yaw angular velocity and the wind speed applied to the vehicle. Here, crosswind was applied for 1 s, and the velocity of the moving vehicle was set to be 40–100 km/h. The results show that the yaw angular velocity increases as the wind speed and the velocity of a moving vehicle increases. Fig. 4(b) shows the lateral displacement of the moving vehicle subjected to the crosswind. The crosswind with the speed of 25 m/s was applied to the moving vehicle for 1 s. As the moving speed of the vehicle increases, the course deviation also increases. In this numerical simulation, the reaction of the driver is not considered. Therefore, the vehicle draws a line with a slope even when the crosswind is not applied.

The objective of this study is the investigation of the stability of moving vehicles under strong crosswind. The overturning is one of the most important problems for moving stability. In this study, however, the overturning of the vehicle cannot be predicted properly because the aerodynamic drag force and rolling moment induced by strong crosswind are not considered in this study. Cai and Chen [11] developed a framework to consider different types and arbitrary number of vehicles on the bridge, and a comprehensive analysis of vehicle accidents on bridges and highways including overturning was performed [12]. A further investigation is necessary in this regard.

3. Driving simulator experiment on the behavior of a moving vehicle under crosswind

3.1. Relationship between gust wind speed and averaging time

The closure of expressways in Japan is determined by the average wind speed for 10 min. However, vehicles on the expressway are subjected to the gust wind. The gust wind speed is greater than the average wind speed for 10 min.

Fig. 5(a) shows the wind speed recorded at Kashiwa Campus of The University of Tokyo while a typhoon was passing on October 1, 2002. The height of the observation point is 10 m. The average wind speed for 100 min is 8.9 m/s. The maximum average wind speed for 10 min is 11.2 m/s and the minimum average wind speed for 10 min is 7.6 m/s as shown in Fig. 5(a). Fig. 5(b) shows the ratios between the average wind speeds with various averaging time and the average wind speed for 10 min. The ratios increase as the averaging time decreases. When the averaging time is set to be 2 s, the wind speed exceeds the double of that for 10 min in some time windows.

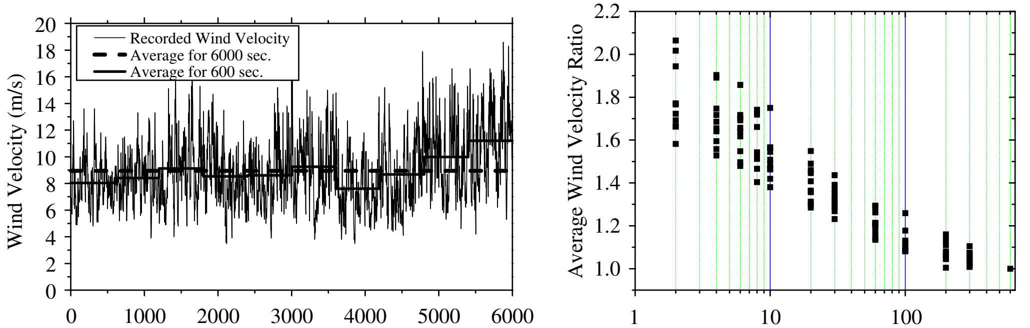

Fig. 5. (a) Wind speed time history recorded at Kashiwa Campus, The University of Tokyo, and (b) the ratios between the average wind speed for 10 min and those for various averaging time.

3.2. Comparison between driving simulator experiment and actual vehicle test

The reactions of a driver under strong crosswind are not considered in the numerical simulations conducted in this study. It is important to grasp the response characteristics of a moving vehicle subjected to crosswind. However, it is necessary to investigate the drivers' reactions because a vehicle can run the aimed course only when it is controlled by a driver. To achieve this objective, a series of virtual tests were conducted using the driving simulator, which was installed in the Institute of Industrial Science, The University of Tokyo (Fig. 6). A scenario highway course is programmed in the simulator for virtual driving. The front view from the driver's seat is realized on three large screens with LCD projectors. The sound system and mirrors give good reality to the simulator. This simulator has six servomotor-powered electric actuators to simulate the motion of a vehicle. Nineteen response variables, e.g., the position of a vehicle, running speed, position of the accelerator pedal and so forth, can be recorded by a personal computer during experiments [1].

With respect to the vehicle responses under crosswind, some researchers have conducted the experiments using vehicle models in the wind tunnel [13,14]. It is necessary to obtain the aerodynamic forces and moments on vehicles in high crosswinds. However, it is also important to grasp the response characteristics of drivers to crosswinds. Therefore, the experiment using a driving simulator is expected to contribute to this issue. The use of wind fences to reduce the risk of traffic accidents around bridge towers was investigated by numerical simulations [15]. The quantitative prediction on the effects of wind barriers in driving performances is still difficult because the driver's reactions should be considered. In this regard, a driving simulator may perform as a useful tool to examine the effectiveness of setting wind barriers.

First, the reproducibility of the experiments using the driving simulator is discussed. The driving condition was set following the experiment using an actual motor vehicle conducted by Kito et al. [16]. They have conducted the experiment on a straight road with the length of 110 m. A moving vehicle was subjected to crosswind generated by huge fans set along a 15 m distance in this real test. Six examinees were employed in our driving simulator experiment. They were requested to drive at the speed of 90 km/h, and crosswind

Fig. 6. Driving simulator used in this study.

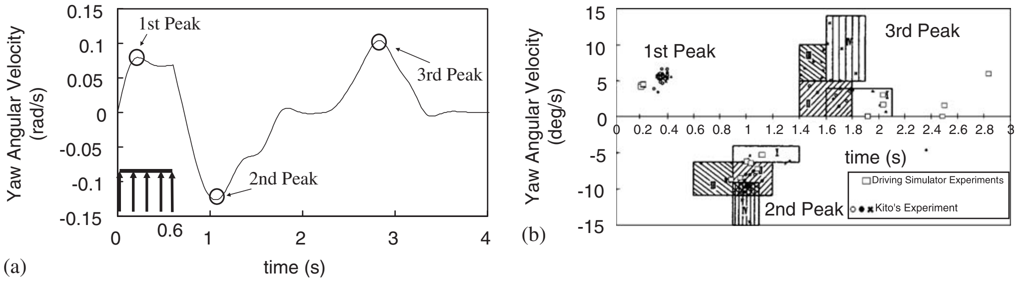

Fig. 7. (a) Three peak values of yaw angular velocity and (b) the comparison between the peak values from the actual vehicle tests by Kito et al. [16] and those obtained from the driving simulator experiments. (I, II, III, and IV are the classifications of drivers' responses by Kito et al. [16]).

with the speed of 22.5 m/s was applied for 0.6 s (in accordance with 15 m distance). These driving conditions are equivalent to the actual vehicle tests conducted by Kito et al. [16].

As shown in Fig. 7(a), the three peak values of yawing velocity and their associated times were extracted. The first peak is related to the yawing moment generated by crosswind, and the others are related to the reactions of the drivers. The results obtained from the driving simulator experiment were compared with those obtained from the experiment using an actual motor vehicle in Fig. 7(b). In the figure, the first peak values obtained from the driving simulator are seen at around 0.2 s, and those from the actual vehicle test are seen at around 0.35 s. The time lag between two experiments is about 0.15 s. When a vehicle is moving at the speed of 90 km/h for 0.15 s, it runs about 4 m, which is almost equal to the length of a compact car. The aerodynamic forces because of crosswind were applied to the center of gravity of a vehicle from the beginning in the driving simulator experiment. On the other hand, in the actual vehicle test, a moving vehicle is subjected to crosswind from the front face, and the whole part of a vehicle was subjected to crosswind in 0.15 s. Therefore, this fact explains the time lag of the first peak values between the two experiments.

The time and the value of the second peak are similar for both experiments. In the third peak, the values obtained from the driving simulator experiment are smaller than those from the actual vehicle test. The associated time is longer than that of the actual test. This is because the width of the road was set to be 1.95 m in the actual vehicle test, which is narrower than the width of an ordinary road (3.6 m). The drivers have to turn the steering wheels earlier to keep their running lane in the actual test. Based on these comparisons, it is expected that the results from the driving simulator experiment show the equivalent results of the actual vehicle test.

3.3. *Driving simulator experiment and numerical simulation of moving vehicle under crosswind considering driver's reactions*

Thirty-three examinees took part in our simulator experiment. Table 2 shows the distribution of age and driving frequency of the examinees. The examinees have a broad range of age and driving frequency. Each examinee was requested to drive only once. Since the running speed of a vehicle was set to be either 80, 100 or 120 km/h, the examinees were divided into three groups. The uniform crosswind with 2 s duration was applied from left

Table 2
Distribution of the age and the driving frequency of the examinees

Age	Seldom or never	A few times a month	A few times a week	Almost everyday	Total
−20	1	0	0	0	1
21–30	5	3	3	1	12
31–40	3	1	2	2	8
41–50	1	1	2	1	5
51–	0	1	5	1	7
All	10	6	12	5	33

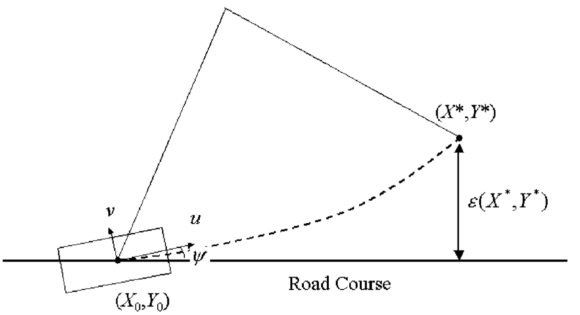

Fig. 8. Outline of the second-order predictable correction model.

to right while the vehicle was moving on a straight section. As mentioned before, the wind speed for expressways closure is 25 m/s, but the closure of an expressway may start when the average wind velocity becomes 15 m/s. Therefore, the wind speed in our test was set to be either 15, 22.5 or 30 m/s.

There are some numerical models considering the interaction between the motion of a vehicle and the response of a driver. In this study, the second-order predictable correction model proposed by Yoshimoto [17] was used in numerical simulation of the response of a moving vehicle subjected to crosswind. It is shown that the second-order predictable correction model is more suitable than other numerical models when the vehicle is moving at high speed [17]. Thus, the simulated responses by the second-order predictable correction model were compared with the results from the driving simulator experiments. Fig. 8 shows the outline of Yoshimoto's model, which assumes that drivers can respond not only to the direction of the velocity but also to the change in the direction of velocity because they feel the inertial force due to acceleration. Based on this assumption, the position of the vehicle at time τ, (X^*, Y^*), from the present position, (X_0, Y_0), can be predicted by Eqs. (6) and (7):

$$X^* = X_0 + \int_0^{\tau} \{u \cos(\Psi + \dot{\Psi} t) - v \sin(\Psi + \dot{\Psi} t)\} \mathrm{d}t, \tag{6}$$

$$Y^* = Y_0 + \int_0^{\tau} \{u \sin(\Psi + \dot{\Psi} t) + v \cos(\Psi + \dot{\Psi} t)\} \mathrm{d}t, \tag{7}$$

Table 3
Parameters for the second-order predictable correction model.

Parameter	Definition	Value	Unit
T	The sampling period for turning steering	0.6	s
I	The mass moment of inertia of steering system	11.8	N m s^2/rad
C	The damping coefficient of steering system	882	N m s/rad
K_{st}	The elastic constant of the steering	48.5	kN m/rad
r	The radius of steering wheel	0.2	m

where X^* and Y^* are the predicted future positions of the longitudinal and transverse components in the absolute coordinate, respectively. Then, the course deviation ε at τ can be obtained. It is also assumed that the driver produces the steering force proportional to the course deviation (with the proportional constant, H) and that the reaction is performed for time interval T. Since the constant steering force is produced for the period of T, the expectation of the time delay for the motion is equivalent to $T/2$ [17]. Based on this assumption, the steering force performed by the driver with time interval T can be obtained by

$$f = H\varepsilon, \tag{8}$$

where f is the steering force performed by the driver. According to this procedure, the steering angle is described as

$$In\frac{\mathrm{d}^2A}{\mathrm{d}t^2} + Cn\frac{\mathrm{d}A}{\mathrm{d}t} + K_{\mathrm{st}}(nA - \delta_{\mathrm{t}}) = \frac{fr}{n}, \tag{9}$$

where I, C and K_{st} are the mass moment of inertia, damping coefficient, and elastic coefficient of a steering system, respectively; n is the inverse of the overall steering ratio, which is a function of running velocity of a vehicle. In this study, n was set as 1/16 for 80 km/h, 1/15 for 100 km/h and 1/14 for 120 km/h in the same manner as that programmed in the driving simulator; r is the radius of the steering wheel and A the steering angle. δ_t is the angular difference between the longitudinal direction and the direction of the front tires, and it is denoted as

$$\delta_t = nA + (\mathrm{SAT}_{11} + \mathrm{SAT}_{12})/K_{\mathrm{st}}, \tag{10}$$

where SAT is the self-aligning torque [7] obtained by the same procedure as in our previous study [9]. Table 3 shows the parameters used for the numerical simulation.

Thus, the three parameters, τ, H and T, are related to the driver's reaction in Yoshimoto's model. These parameters have to be determined properly to obtain good prediction on a moving vehicle subjected to crosswind. In this study, these parameters were calibrated based on the results of the driving simulator experiment. Following the original Yoshimoto's model [15], T was set to be 0.6 s, and H was changed proportionally to T/τ^2 as

$$H = \frac{8}{3}\frac{T}{\tau^2}, \tag{11}$$

where the unit of H is kgf. The proportionality constant in Eq. (11) was obtained from Ref. [17]. Fig. 9(a) shows the relationship between τ, which is related to the reaction of the driver in Yoshimoto's model, and the simulated running trajectories of the vehicle. In the

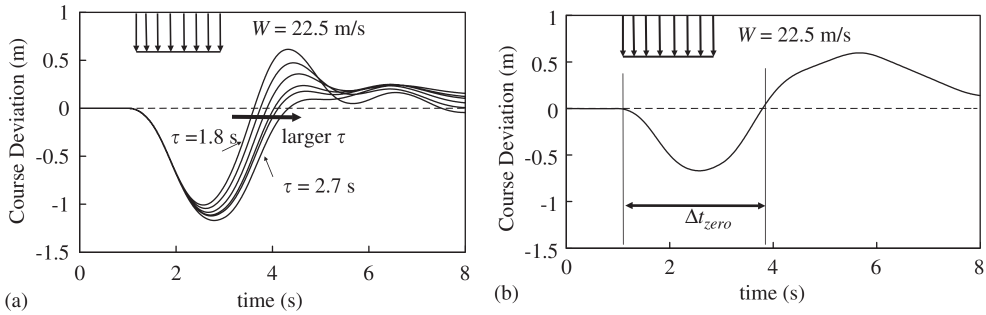

Fig. 9. (a) Relationship between the values of parameters related to the reaction of driver in Yoshimoto's model and the simulated lateral displacements of the moving vehicle (80 km/h) and (b) the example of the lateral displacement obtained from the driving simulator experiment.

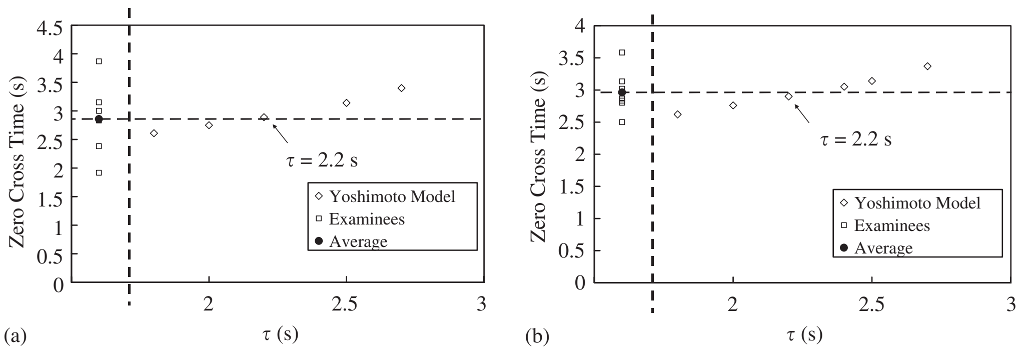

Fig. 10. Comparison of the time to cancel the course deviation obtained from the numerical simulation and driving simulator experiments (vehicle speed: 80 km/h; wind speed: (a) 15 m/s, (b) 22.5 m/s).

figure, τ is changed from 1.8 to 2.7 s. The results show that the time (Δt_{zero}) to cancel the course deviation generated by crosswind increases as τ increases. As shown in Fig. 9(b), Δt_{zero} was extracted from the result of each driving simulator experiment. Fig. 10 shows the comparison between Δt_{zero} obtained from the experiments and those obtained from the numerical simulations for different τ. In the figure, the running speed of the vehicle is 80 km/h, and the wind speeds are 15 and 22.5 m/s. When τ is set to be 2.2 s, Δt_{zero} of Yoshimoto's model is almost equal to the average of Δt_{zero} obtained from the experimental results. Following the same procedures, τ was set to be 2.0 and 1.8 s when the running speed of a vehicle was 100 and 120 km/h, respectively.

Using the parameters related to driver's reactions, which are determined through the procedure shown above, the responses of the moving vehicle subjected to crosswind including driver's reactions were obtained numerically. Fig. 11 shows the comparison between the numerically simulated responses of the moving vehicle subjected to crosswind and the results from the driving simulator experiment. In the figure, the lateral displacements and steering angles were selected as the indices of the responses. The thin lines show the results of the driving simulator experiments, and the thick lines show the predicted responses of the moving vehicle using Yoshimoto's model. The number of examinees is six for the vehicle speed of 100 and 120 km/h, and seven for 80 km/h. The

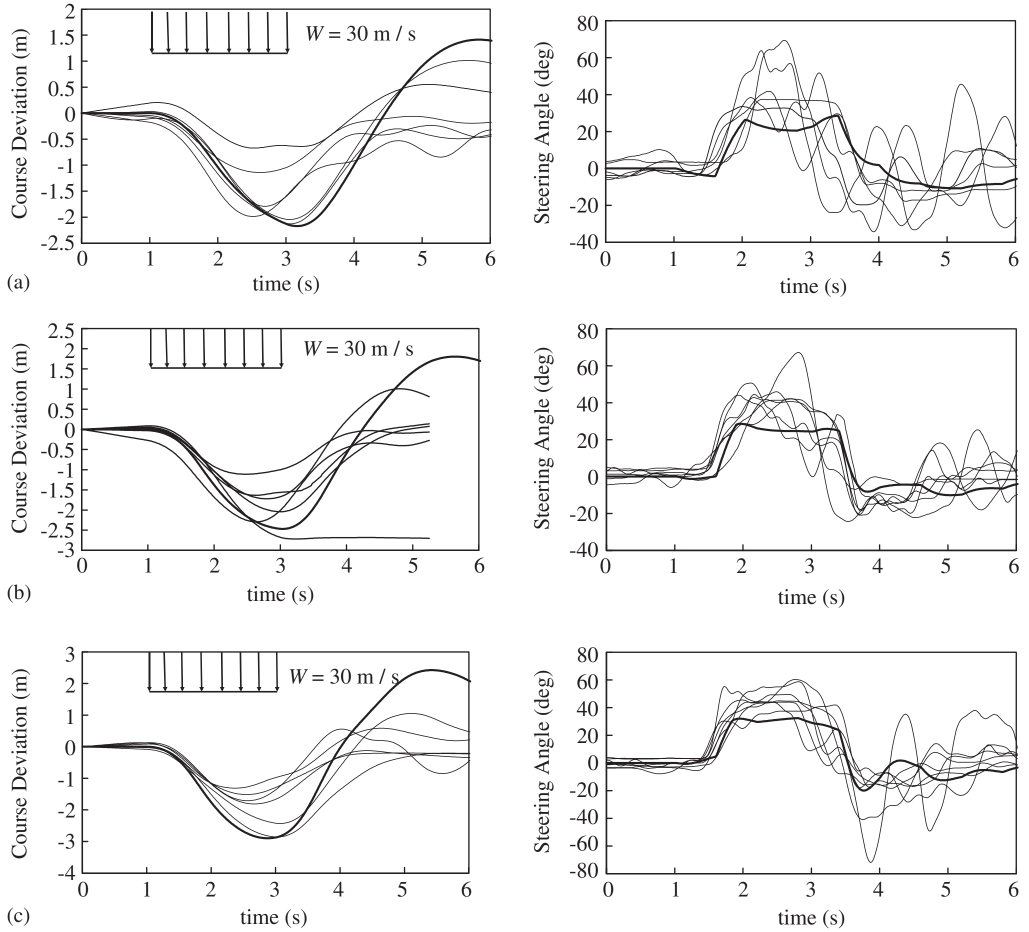

Fig. 11. Comparisons between the simulated responses of the moving vehicle subjected to crosswind using Yoshimoto's model (bold lines) and the results from driving simulator experiments (thin lines) (vehicle speed: (a) 80, (b) 100 and (c) 120 km/h; wind speed: 30 m/s).

numerically simulated results show good agreement with those obtained from the driving simulator experiments.

It is expected that the numerical simulation can predict the lateral displacements of the moving vehicle subjected to crosswind including the driver's reaction. Fig. 12 shows the relationship between the responses of the vehicle and the wind speed applied to the vehicle. In this numerical simulation, the crosswind is applied for 2 s. Maximum yaw angle and course deviation increase as the moving speed of the vehicle and the wind speed increase. In Japan, the width of a single lane of expressways is 3.6 m. The width of the vehicle is about 1.7 m. Therefore, the course deviation of 1 m indicates that the moving vehicle protrudes the running lane. If the traffic is heavy, there may occur some traffic accidents. Based on this assumption, the vehicle protrudes the running lane if the wind speed is about 22 m/s for the vehicle speed of 80 km/h, and about 12 m/s for the vehicle speed of 120 km/h.

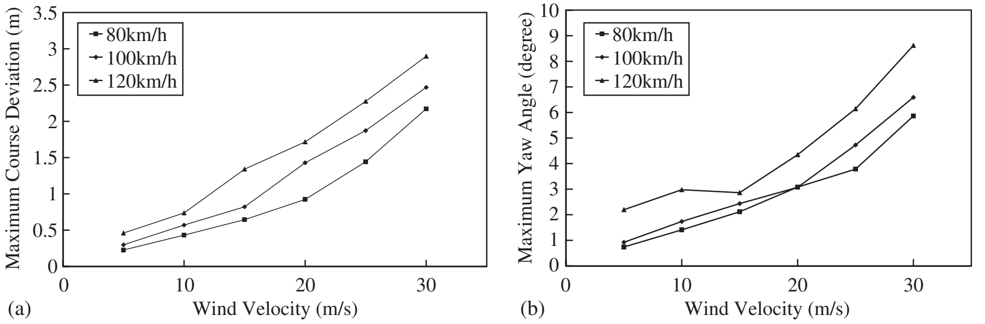

Fig. 12. Relationship between the wind speed and the responses of the moving vehicle obtained from numerical simulation.

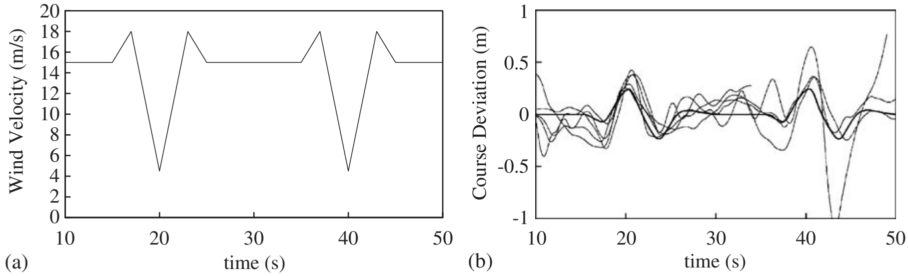

Fig. 13. (a) Crosswind applied to the moving vehicle and (b) the comparison between the lateral displacements obtained from driving simulator experiments (thin lines) and that from Yoshimoto's model (bold line) (vehicle speed: 100 km/h).

Charuvisit et al. [18] tried to obtain the vehicle responses under crosswind using the second-order predictable correction model, similar to this study. In the study, however, the numerical simulation did not show convincing results. The physical tire model used by the study has a linear relationship between the force produced by each tire and the slip angle. On the other hand, the non-linear tire model called Magic Formula Model [8] is employed in this study. The characteristics of the physical tire model may reflect the differences in the results of numerical simulations.

4. Effects of the change of wind speed on the responses of moving vehicles

So far, the responses of a moving vehicle subjected to uniform crosswind were discussed. It is reported that the drivers find it difficult to control their vehicles where the wind speed changes abruptly, e.g., at the exit of a tunnel, at the gap of wind barriers, in the wake of a bridge tower and so on. Therefore, the crosswind whose speed changes sharply was employed for the driving simulator experiment. Fig. 13(a) shows the crosswind applied to the vehicle, which models the characteristics of wind velocities along the vehicle path behind the bridge tower [19], and Fig. 13(b) shows the course deviations of five examinees (thin lines). In the experiment, the examinees were instructed to drive at the speed of 100 km/h, and the crosswind was applied from left to right. If the vehicle moving on the bridge is subjected to strong crosswind, the wind-induced vibration of the bridge may have some effects on the moving stability of the vehicle. To grasp the effect of crosswind on the moving vehicle clearly, the vibration of the bridge is not considered in this study.

The thick line in Fig. 13(b) shows the result of numerical simulation using Yoshimoto's model. The parameters related to driver's response are set to be the same as those determined in the previous chapter. Although the parameters were determined based on the experimental results for the uniform crosswind, the predicted response of the moving vehicle shows good agreement with the results of examinees. Therefore, it is expected that the numerical simulation is helpful to grasp the trend of vehicle's behavior under crosswind. Charuvisit et al. [18] showed that the conventional quasi-steady method does not predict the yawing moment properly when the wind speed changes sharply. It is necessary to accumulate the results of experiments for predicting transient state aerodynamic coefficients.

The crosswind whose speed is not constant is shown in Fig. 14(a). The wind speed changes sharply from 25 to 0 m/s in Case 1, and it changes gradually in Case 4. The shape representing the decreasing wind speed, w, is obtained by

$$w = \frac{w_0}{2}\cos\frac{X}{D}\pi + \frac{w_0}{2}, \tag{12}$$

where w_0 is the constant wind speed, which is set to be 25 m/s in this study; X the longitudinal position of the vehicle subjected to the crosswind whose speed is decreasing; and D the distance where the wind speed changes. D is set to be 50, 100, 300 and 500 m in Cases 1–4, respectively. The wind speed increases symmetrically as shown in Fig. 14(a).

The numerical simulations considering the driver's reactions were conducted using Yoshimoto's model. The parameters related to the driver's response were set as those determined in this study. The moving speed of the vehicle is 100 km/h. Fig. 14(b) shows the lateral displacements of the moving vehicle subjected to the crosswinds shown in Fig. 14(a). In the figure, the course deviation increases as the wind speed changes more sharply.

This numerical simulation can predict the vehicle behavior when it is subjected to crosswind without conducting many experiments using an actual vehicle or a driving simulator. It is expected that this research will contribute to decision-making on the efficient setting of wind barriers and expressways closure.

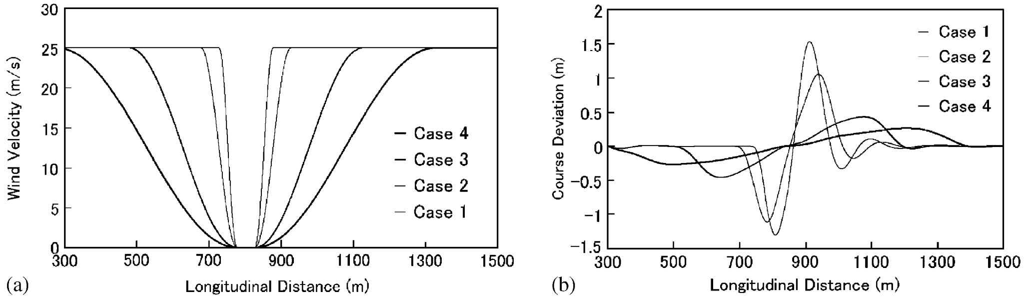

Fig. 14. (a) Crosswind applied to the moving vehicle and (b) the lateral displacements obtained from Yoshimoto's model (vehicle speed: 100 km/h).

5. Conclusions

Numerical simulations and driving simulator experiments were conducted to investigate the moving stability of a vehicle subjected to crosswind. The results of the driving simulator experiments were compared with those obtained from the experiments using an actual automobile. The three peak values of yawing angular velocities and their associated times were extracted from the results of the driving simulator experiments, and their distribution was compared with that from the actual vehicle tests. Based on the comparison, it is expected that the driving simulator experiments can well produce the equivalent moving conditions in the actual environment.

Thirty-three examinees participated in the driving simulator experiment. The results obtained from the experiments were compared with those simulated by a numerical model that can consider the interaction between the vehicle motions and driver's reactions. If the parameters related to the driver's responses are determined properly based on driving simulator experiments, the simulated responses of the moving vehicle will show good agreement with those obtained from the driving simulator experiments.

Hence, if the model parameters related to driver's reactions are properly determined, the responses of a vehicle under crosswind can be simulated systematically using the numerical model without conducting a large number of actual vehicle tests and driving simulator experiments. For a further study, various types of vehicle models should be considered to make more general conclusions. The vehicle model used in this study is designed for a compact car. A large-sized vehicle is subjected to larger aerodynamic forces during strong crosswind. Therefore, it is necessary to make some types of vehicle models and investigate the responses under crosswind. The method proposed in this research will contribute to decision-making on the expressway closure under strong wind and the design of wind barriers.

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