AUTOMOBILE DRIVERS' RESPONSES TO LATERAL WIND DISTURBANCE BASED ON DRIVING SIMULATOR EXPERIMENTS

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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 running 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 drivers feel difficulty in controlling their vehicles. This study investigates the running stability of a vehicle under strong crosswind based on numerical analyses and driving simulator experiments. First, the physical responses of a moving vehicle under strong crosswind are evaluated. According to the results, it is observed that the vehicle skidded due to the strong wind when moving at a high speed. 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 (Maruyama and Yamazaki 2003). The driving simulator, which was developed by Mitsubishi Precision Co., Ltd, was installed in the Institute of Industrial Science, the University of Tokyo in 1999. It 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.

As an important factor that affects safety driving on expressways, strong crosswind should be taken into consideration. Japan Highway Public Corporation (JH) owns expressway networks with a total length of 6,959 km (as of April, 2002). In expanding expressway networks, various types of structures have been constructed, e.g., long span bridges and bridges with high piers. Vehicles in the wake of bridge towers are subjected to sudden changes of wind speed, and some drivers make traffic accidents (Kimura *et al.* 2001). Large-sized vehicles are sometimes reported to be overturned due to strong crosswind when a typhoon is approaching. In addition, drivers feel difficulty in controlling their vehicles when the wind speed changes abruptly, for example, when they are at the exit of a tunnel, at 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 minutes is larger than or equal to 25 m/s in an ordinal case. However, this regulation level is determined experientially. In fact, if the average wind speed for 10 minutes becomes larger than 15 m/s, highway police officers and JH officers will judge closure of expressway after trials of driving.

Expressway structures are generally well designed for external dynamic forces caused by strong wind. However, the running stability of a vehicle subjected to crosswind is not investigated quantitatively. As a measure to avoid

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the traffic accidents due to strong crosswind, installing wind barriers is effective, but sometimes it increases the wind load to expressway structures.

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

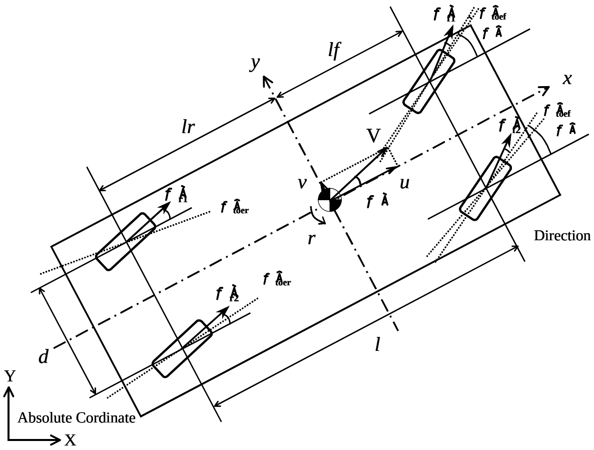


Figure 1. Coordinate System of A Vehicle Model Used in This Study

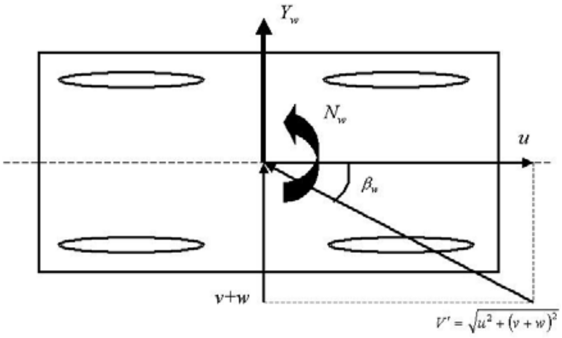


Figure 2. Aerodynamic Forces Acting on The Moving Vehicle

2. NUMERICAL SIMULATIONS ON A VEHICLE UNDER STRONG CROSSWIND

Figure 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 disturbances of road surface are not considered in this study. The equations of motion of a moving vehicle are described as

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

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

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

where u and v are the vehicle velocities in the longitudinal and transverse directions, respectively. ψ is the yaw angle, and δ_t is 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 (Bakker *et al*. 1989). The index *i* represents the front or rear wheel and the index *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 used in our previous study (Maruyama and Yamazaki 2002).

As shown in Fig. 2, when a moving vehicle is subjected to crosswind, lateral force, Y_w, and yawing moment, N_w, are generated as

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

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

where S is the front area of the vehicle, and ρ is the density of air. w is the wind speed. 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 (Fig. 2).

Substituting the aerodynamic forces obtained from Equations (4) and (5) to the equations of motion of a vehicle (Equations (2) and (3)), numerical simulation on the moving vehicle subjected to crosswind can be conducted.

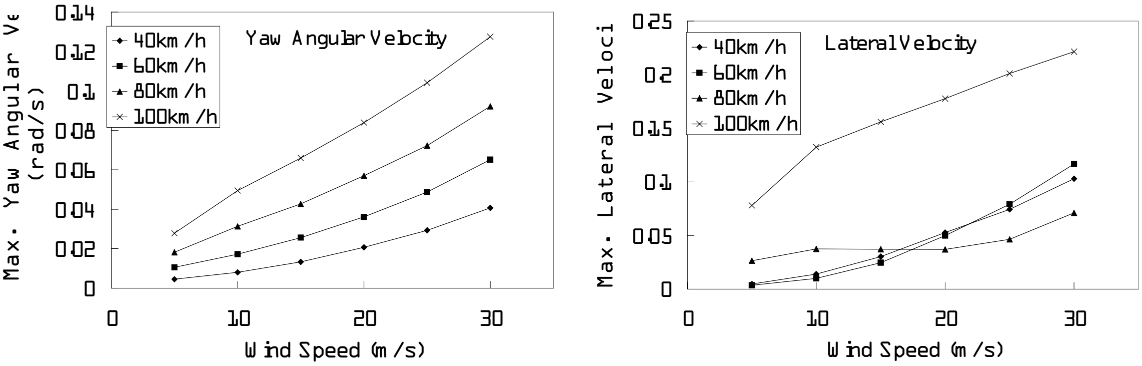


Figure 3. Relationships Between The Maximum Yaw Angular Velocity of The Moving Vehicle and The Wind Velocity Applied to The Vehicle (left), and Between The Maximum Lateral Velocity of The Moving Vehicle and The Wind Velocity (right)

All parameters of the vehicle model are set to be the same as those used in the driving simulator. The vehicle model of the simulator is designed for a compact car. Figure 3 shows the relationships between the maximum response of the moving vehicle and the wind speed applied to the moving vehicle. Here, crosswind was applied for 1 s, and the velocity of the moving vehicle was set to be 40 km/h-100 km/h. The results show that the yaw angular velocity becomes larger as the wind speed and the velocity of a moving vehicle become larger. On the contrary, the maximum lateral velocity is large only when the velocity of the moving vehicle is 100 km/h. It seems that the vehicle is skidding because a large centrifugal force is applied to the moving vehicle due to a large yawing moment when the vehicle is moving at the speed of 100 km/h or larger speeds.

Figure 4. Overview of The Driving Simulator Used in This Study

Table 1. 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

3. VIRTUAL TESTS USING DRIVING SIMULATOR UNDER STRONG CROSSWIND

In the numerical simulation conducted in the previous chapter, the reactions of a driver are not considered. 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, Japan (Fig. 4). This driving simulator was developed by Mitsubishi Precision Co., Ltd. A scenario highway course is equipped with the simulator for virtual driving. The front view from the driver's seat is realized by 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 (19) 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.

With respect to the vehicle responses under crosswind, some researchers have conducted the experiments using an actual motor vehicle in a natural environment. However, it is difficult to give the same conditions to all examinees, especially regarding wind speed. If a huge fan to produce wind artificially is employed for experiments, examinees can know the position where they get aerodynamic forces. Therefore, the experiment using a driving simulator is expected to contribute to this issue. The use of wind fences to reduce the risk of accidents around bridge towers is sometimes investigated using wind tunnel tests (Phongkumsing *et al.* 2001). However, quantitative prediction on the effects of a wind barrier to driving performance is still difficult. In this regard, a driving simulator is possible to be a useful tool to examine the effectiveness of setting a wind barrier.

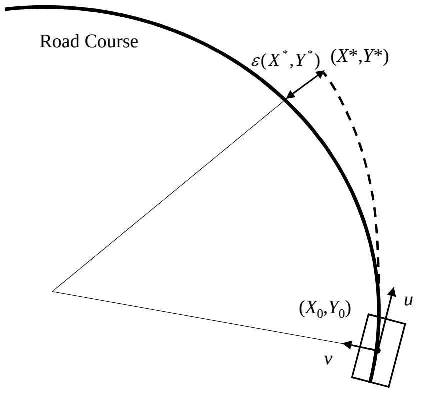


Figure 5. Outline of The Second-Order Predictable Correction Model

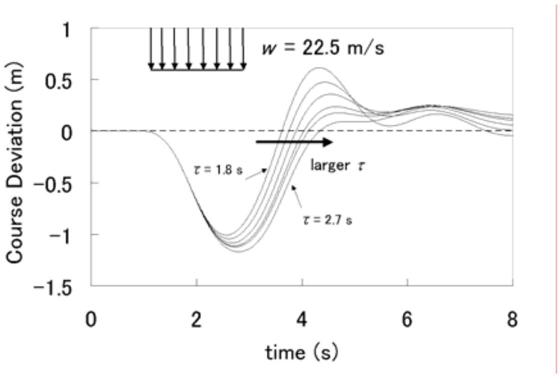


Figure 6. Relationship Between The Values of Parameters Related to The Reaction of The Driver in Yoshimoto's Model and The Simulated Running Trajectories of The Vehicle (80 km/h)

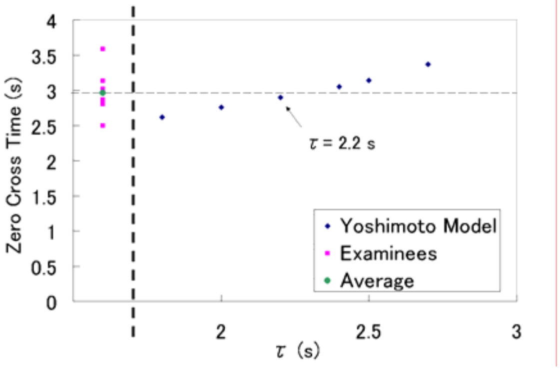


Figure 7. Comparison of The Time to Cancel The Course Deviation Obtained from The Numerical Simulation and Driving Simulator Experiments (vehicle speed: 80 km/h, wind speed: 22.5 m/s)

Thirty-three (33) examinees participated in the experiment using the driving simulator. Table 1 shows the distribution of the age and the 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 km/h, 100 km/h or 120 km/h, the examinees were divided into three groups. The uniform crosswind with 2 s' duration was applied from left to right while the vehicle was moving on a straight section. The wind speed was set to be either 15 m/s, 22.5 m/s 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 (1968) was used in numerical simulation on the response of a moving vehicle subjected to crosswind. Then, the simulated responses of the moving vehicle were compared with the results from the driving simulator experiments. Figure 5 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 Equations (6) and (7).

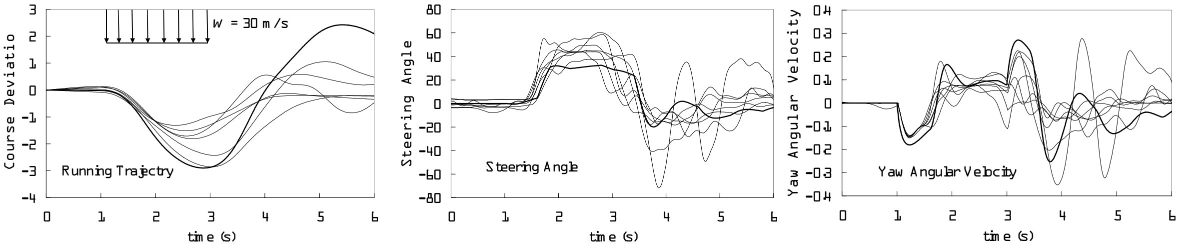
$$X^* = X_0 + \int_0^{\tau} \{u\cos(\psi + \dot{\psi}t) - v\sin(\psi + \dot{\psi}t)\}dt \quad (6)$$

$$Y^* = Y_0 + \int_0^{\tau} \{u\sin(\psi + \dot{\psi}t) + v\cos(\psi + \dot{\psi}t)\}dt \quad (7)$$

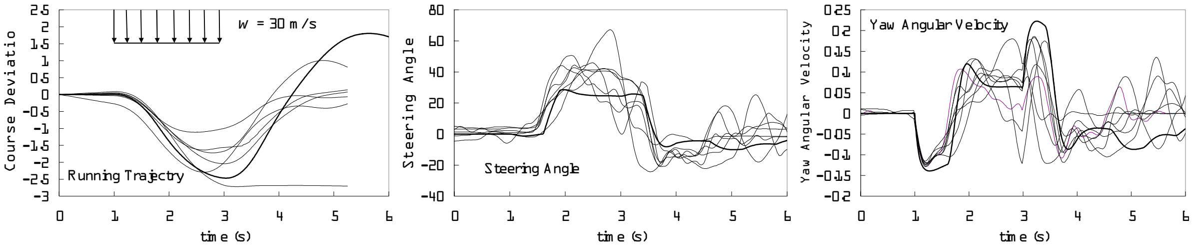
It is also assumed that the driver produces a constant steering force proportionally to the course deviation, ε, with the proportional constant, H, and the steering force is constant for the period of T. Therefore, the three parameters, τ, H and T, are related to the driver's reaction in Yoshimoto's model. These parameters have to be determined properly to obtain good prediction on a moving vehicle subjected to crosswind.

In this study, T was set to be 0.6 s following the original Yoshimoto's model, and H was changed proportionally to T/τ^2 (Yoshimoto 1969). Figure 6 shows the relationship between the value of τ, which is related to the reaction of the driver in Yoshimoto's model, and the simulated running trajectories of the vehicle. The results show that the time (Δt_{zero}) to cancel the course deviation generated by crosswind becomes longer as τ becomes larger. The Δt_{zero} was also extracted from the results of experiments. Figure 7 shows the comparison between Δt_{zero} obtained from the experiments and those obtained from the numerical simulations for different τ. In this case, the running speed of the vehicle is set to be 80 km/h. According to the figure, when τ is set to be 2.2 s, Δt_{zero} is determined as the average of the experimental results. Considering the results from other wind speeds (15 m/s and 30 m/s), the suitable value of τ was also 2.2 s. Following the same procedures, τ was set to be 2.0 s and 1.8 s when the running velocity of a vehicle was 100 km/h and 120 km/h, respectively.

Figure 8 shows the comparison between the simulated responses of the moving vehicle subjected to crosswind using Yoshimoto's model and the results from the driving simulator experiment. It is observed in the figure that the simulated responses of the moving vehicle show good agreements with those obtained from the driving simulator experiment. Hence, it is expected that the response of a moving vehicle subjected to crosswind can be simulated with high accuracy using a numerical model considering the interaction between the vehicle motion



(a) Vehicle Speed: 120 km/h



(b) Vehicle Speed: 100 km/h

Figure 8. 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) (wind speed: 30 m/s)

and driver's reaction if the parameters related to the driver's responses are properly determined based on driving simulator experiments.

4. CONCLUSION

Numerical simulation and driving simulator experiments were conducted to investigate the running stability of a vehicle subjected to crosswind. Thirty-three (33) examinees participated in the experiment. The results obtained from the experiments were compared with those simulated by a numerical model that can consider the interaction between vehicle motion and driver's reaction. If the parameters related to the driver's responses are determined properly based on driving simulator experiments, the simulated responses of the moving vehicle showed good agreement with those obtained from the driving simulator experiments. Hence, the responses of a vehicle under crosswind can be simulated systematically using the numerical model if the model parameters are properly determined. It is expected that this research is helpful for the decision making of the expressway closure under strong wind and the design of wind barriers.

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