EARTHQUAKE ENGINEERING AND STRUCTURAL DYNAMICS
Earthquake Engng Struct. Dyn. 2004; **33**:775–792 (DOI: 10.1002/eqe.378)

Fundamental study on the response characteristics of drivers during an earthquake based on driving simulator experiments

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SUMMARY

After the 1995 Kobe earthquake, the expressway structures in Japan were retrofitted and they will not now be seriously damaged under a certain level of strong earthquake motion. However, the stability of a moving vehicle has not been investigated yet. It has been reported that drivers feel seismically induced vibrations, especially in the transverse direction of vehicles. Owing to this phenomenon, drivers have some difficulty in controlling the vehicles during strong shaking. For further safety promotion of the expressway networks, it is important to understand the drivers' reactions to seismic motion. The present authors have performed a series of seismic response analyses of a moving vehicle to investigate its response characteristics based on numerical simulation. However, the responses of the driver were not considered in the simulation process. In order to investigate the drivers' reactions during an earthquake, a series of virtual tests were conducted using a driving simulator. This driving simulator has six servomotor-powered electric actuators that control its motions. Several types of tests were carried out for different examinees to investigate drivers' responses while controlling the simulator under seismic motion. The results of this study showed that a larger response time lag to strong shaking and over turning of the steering wheel may shift the vehicle into the next lane. According to this finding, traffic accidents could possibly occur under strong ground shaking in the case of heavy traffic.

KEY WORDS: driving simulator; seismic motion; moving stability; steering angle; cross-correlation coefficient; expressway

INTRODUCTION

As the amount of highway traffic increases, safety requirements for highways significantly increase even at the time of an earthquake. Recent large earthquakes, notably, the 1989 Loma Prieta, 1994 Northridge, and 1995 Kobe earthquakes, have caused heavy damage to expressway structures. Hence, countermeasures against large earthquakes have became one of the most

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Contract/grant sponsor: Sasagawa Scientific Research Grant, Japan Science Society

Received 23 April 2003
Revised 11 August 2003
Accepted 29 October 2003

important issues for highway authorities [1]. After the 1995 Kobe earthquake, new seismometer networks were developed along the expressways in Japan, and traffic will be regulated using the earthquake records from these instruments. However, the current regulations need to be examined since the major structural damage that affects safe driving on an expressway is seldom found under the current regulation level of seismic motions [2, 3].

For efficient traffic control on expressways during earthquake shaking, the effect of seismic motion on automobile driving should also be considered along with the structural damage. Many drivers who have experienced an earthquake on expressways have reported that they felt seismically induced vibrations, especially in the transverse direction [4]. A survey revealed that some drivers mistakenly interpreted the earthquake as a tire blowout, and they could not control the steering wheel properly due to abnormal vibration. The survey also showed that the drivers experience difficulty in controlling their vehicles and they might become involved in an accident because of strong shaking. Hence, to increase highway safety, it is important to evaluate the drivers' reactions under seismic motion.

To achieve this objective, the present authors have performed a series of numerical simulations of a moving vehicle to investigate its seismic response characteristics [5]. However, the reactions of a driver to strong shaking were not considered in this analysis. Although drivers' reactions are an important issue, this problem cannot be studied using actual motor vehicles in a natural environment. Recently, driving simulators that can give examinees the reality of driving have been developed by many organizations, and some of them have a motion base that can simulate acceleration while driving a vehicle [6]. In 1999, a driving simulator that has six servomotor-powered electric actuators was introduced to the Institute of Industrial Science at the University of Tokyo [7]. The availability of this simulator made it possible to conduct a series of virtual driving tests during a simulated earthquake. Based on the obtained results from the driving simulator experiments, the response characteristics of drivers under seismic motion were investigated.

SPECIFICATION OF DRIVING SIMULATOR

Figure 1(a) shows the driving simulator that was installed in the Institute of Industrial Science at the University of Tokyo in 1999. This driving simulator was developed by Mitsubishi Precision Co., Ltd. A scenario highway course is realized on three large screens with LCD projectors, and the sound of a real car is also modeled in the simulator. 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. Initially, the vibrations of a moving vehicle were modeled in the driving simulator. Table I shows the specification of the actuators, which can produce up to $0.5g$ in the acceleration range and about 0.3 m in the displacement range. The system of this driving simulator consists of a host computer linked to other systems, e.g. the sound, graphic, steering systems and so on (Figure 1(b)). The main program of the host computer was then modified in order to apply the absolute response displacement due to seismic ground motion of a moving vehicle to the actuator system. The absolute response displacement was obtained from a previous study of the seismic response analysis of a moving vehicle [5]. In the response analysis, each vehicle model parameter was set to the same value as that used in the driving simulator.

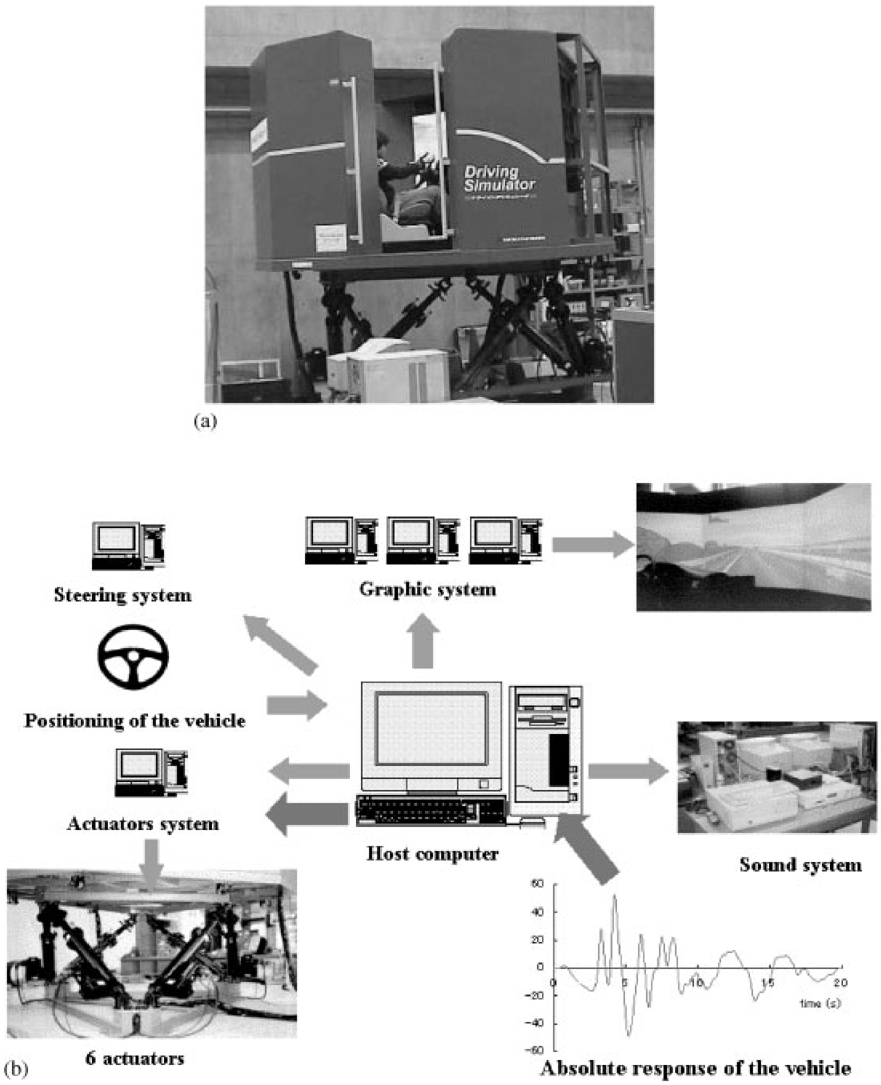

Figure 1. (a) Overview of the driving simulator used in this study; and (b) its system configuration.

Before conducting the virtual driving experiments, the characteristics of the actuator system were investigated. A sinusoidal wave with a specific frequency was applied to the actuators, and the amplitude ratio between the motion applied to the actuators and the motion produced by the actuators was calculated (Figure 2). The amplitude ratio is almost equal to 1.0 in the lower frequency range and gradually decreases as the frequency increases. In the seismic response analysis it was also observed that the amplitude ratio between the ground excitation and the response acceleration of a moving vehicle becomes smaller as the frequency becomes larger [5]. Therefore, the sensitivity of the actuators with respect to the applied motion was

Table I. Specification of the actuators equipped to the driving simulator.

Component	Range	Max. velocity	Max. acceleration
X	−0.3 m to 0.25 m	0.33 m/s	$0.5g$
Y	−0.26 m to 0.26 m	0.35 m/s	$0.5g$
Z	−0.40 m to 0.29 m	0.38 m/s	$0.5g$
Roll	−20 deg to 20 deg	23 deg/s	–
Pitch	−18 deg to 21 deg	21 deg/s	–
Yaw	−17 deg to 17 deg	22 deg/s	–

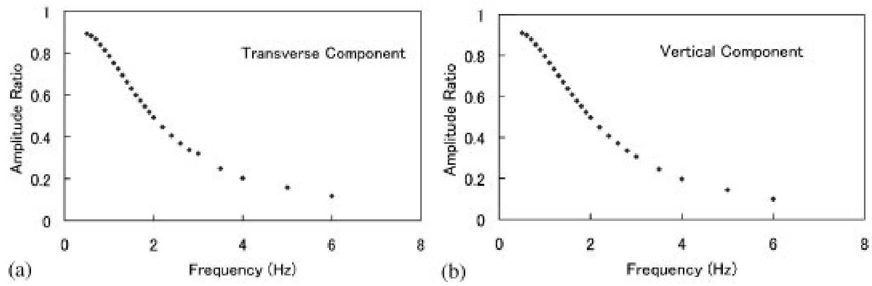

Figure 2. Amplitude ratio between the applied harmonic wave and the motion produced by the actuators: (a) transverse component; and (b) vertical component.

not taken into consideration. It should be noted that although the inverse function of Figure 2 was applied to the seismic response displacement of a vehicle, the motion produced by the actuators became much worse than the motion without applying the inverse filtering.

In order to reveal the reproducibility of motions due to the driving simulator, the motion produced by the actuators was compared to the one applied to the actuators using the records from an accelerometer, which was set in the cabin of the driving simulator. Figure 3 shows the acceleration time histories and the Fourier spectra of the applied motion and produced motion. In this case, the Japan Meteorological Agency (JMA) Kobe record (scaled to $PGA = 2\,\mathrm{m/s^2}$) of the 1995 Kobe earthquake was used as the ground motion. As mentioned earlier, the actuators are controlled using displacement time histories, but the motion produced by the actuators is compared with respect to acceleration time histories. One can see that the Fourier spectrum of the output motion has a peak in the frequency range of 7–8 Hz. When the Chiba Experimental Station record of the 1987 Chiba-ken Toho-Oki earthquake [8] (scaled to $PGA = 2\,\mathrm{m/s^2}$) was used as the ground motion, the peak in the frequency range of 7–8 Hz became much larger than the one shown in Figure 3(b). The Chiba record has larger response spectrum amplitudes in the higher frequency range than the JMA Kobe record [5]. It was found that this peak becomes larger when the ground motion has a larger amplitude in the higher frequency range. These results indicate that the driving simulator vibrates itself in the 7–8 Hz frequency range, which may be caused by the surrounding walls of the cabin of the driving simulator vibrating resonantly in this frequency range.

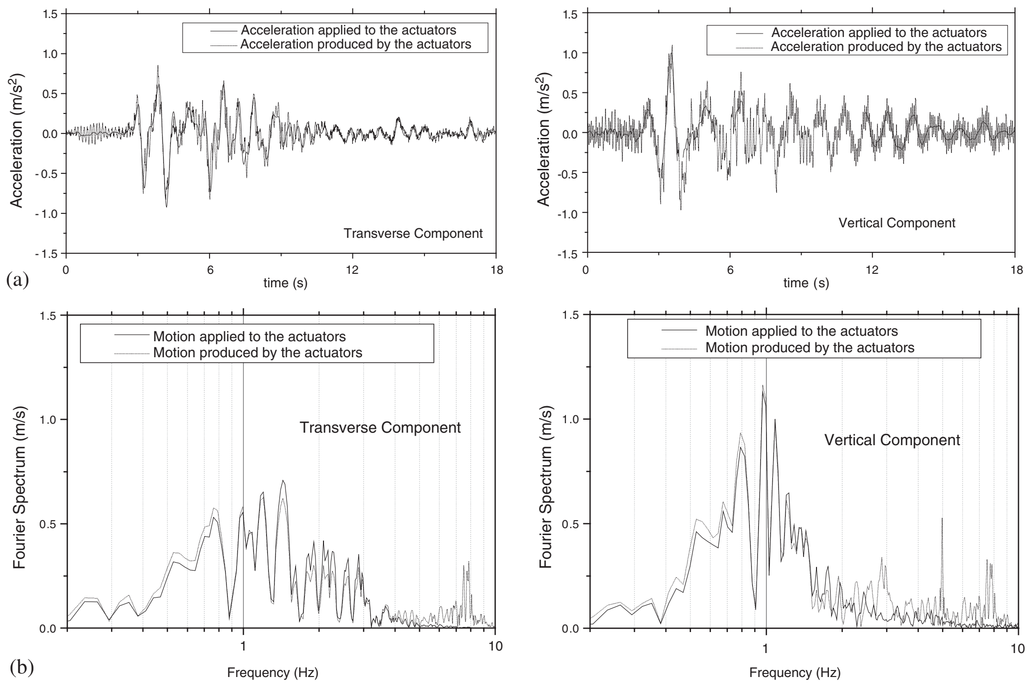

Figure 3. Comparison between the motion applied to the actuators and the motion produced by the actuators of the driving simulator. The JMA Kobe record scaled to $PGA = 2\,\mathrm{m/s^2}$ was used as ground motion: (a) acceleration time histories; and (b) fourier spectra.

VIRTUAL DRIVING TESTS DURING AN EARTHQUAKE USING THE DRIVING SIMULATOR

Procedure of experiments

Considering the reproducibility of motion by the driving simulator, the JMA Kobe, SCT Mexico [9] (filtered in the range of 0.2–5.0 Hz) and El Centro [9] (filtered in the range of 0.2–3.0 Hz) records were selected as ground motions. Each ground motion record was scaled with respect to the Peak Ground Acceleration (PGA) of the vehicle's transverse direction. Figure 4 shows the absolute response acceleration time histories of a running vehicle used for the experiments.

Two kinds of experiments were conducted, the first of which aims to clarify the characteristics of drivers' responses to different intensities of seismic motion. Ten examinees were selected for this experiment and each was requested to drive one time through each of the three types of selected ground motions, which have different seismic intensities. Three tests were conducted for each examinee at intervals of ten minutes or so to avoid getting accustomed to driving during shaking. The second experiment aims to reveal the characteristics of drivers' responses to the ground excitation with respect to the different driving frequencies and the ages of the examinees. Thirty-three examinees were selected for this experiment and each examinee was requested to drive only once.

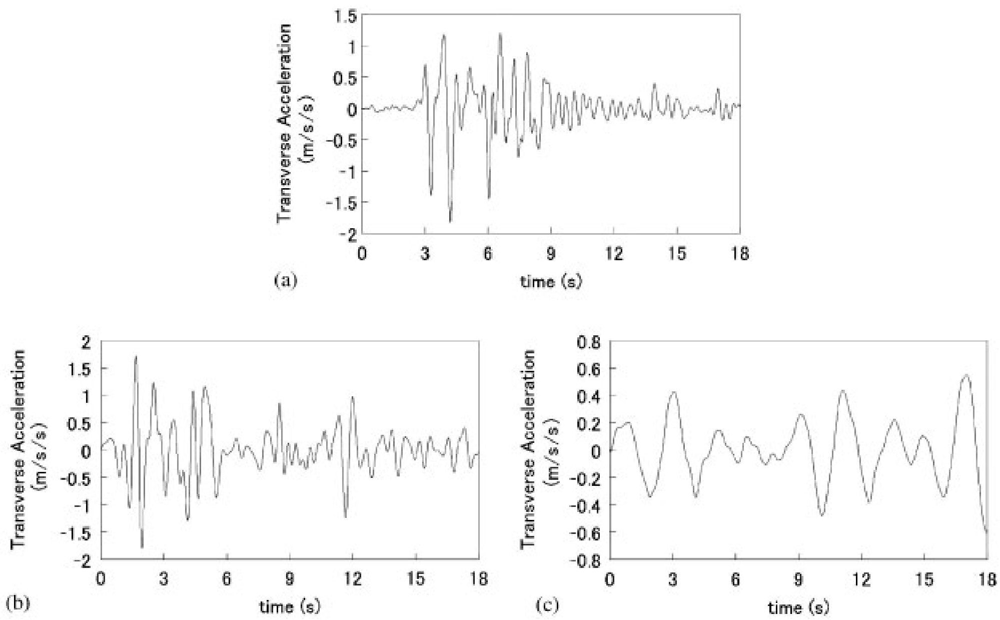

Figure 4. Absolute response acceleration time histories to the transverse direction of a running vehicle under seismic motion. The JMA Kobe and the El Centro records were scaled to $PGA = 4\,\mathrm{m/s^2}$, and the SCT Mexico record was scaled to $PGA = 1\,\mathrm{m/s^2}$: (a) JMA Kobe; (b) El Centro; and (c) SCT Mexico.

Before conducting the test, the aim of both experiments in this study was explained to the examinees. In addition, when the examinees were on the driving simulator, their driving behaviors might have been different from those in usual situations. Therefore, the results of the experiments may be biased to some extent. However, to remove such a bias is almost impossible for tests using a simulator.

For both experiments the examinees were instructed to drive at a speed of 100 km/h, which is the maximum legal speed in Japan, and to drive in the left lane. The road surface was assumed as being dry. Three other vehicles were inserted into the scenario highway course as shown in Figure 5(a), and an earthquake motion was given at the position of the scenario course whilst the vehicle was moving in a straight direction, as in Figure 5(b). Note that the North–South components of the real earthquake records are considered as the transverse components. All input seismic motions are the records obtained from free fields because this research aims to investigate the fundamental tendencies of drivers' responses to seismic motion. When a test during driving on an elevated viaduct is conducted, the input motion should be modified to take account of the responses of the viaduct. The reactions of the examinees were recorded by a personal computer during the experiments. The simulator can record a total of 19 response variables, e.g. the position of the vehicle, running speed, position of the accelerator pedal and so on. In this study, the reactions of the examinees were investigated mainly using the steering angular velocity and the steering angular acceleration. The examples of steering angular velocity are plotted in Figure 6, where the reactions are seen to be large as the input accelerations become large.

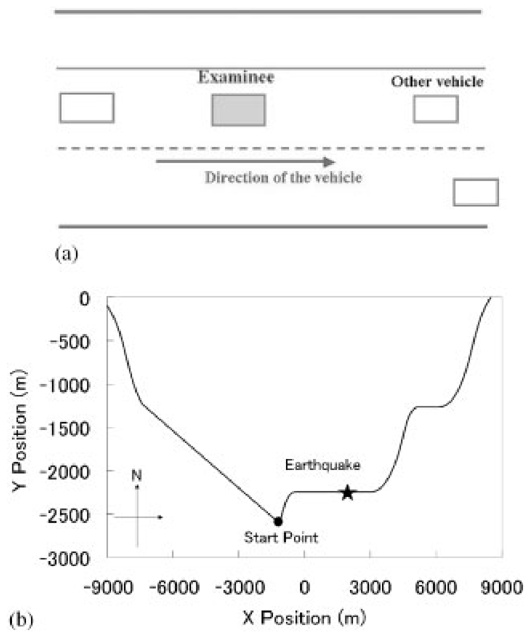

Figure 5. (a) Driving condition in the experiment; and (b) the scenario highway course programmed into the driving simulator.

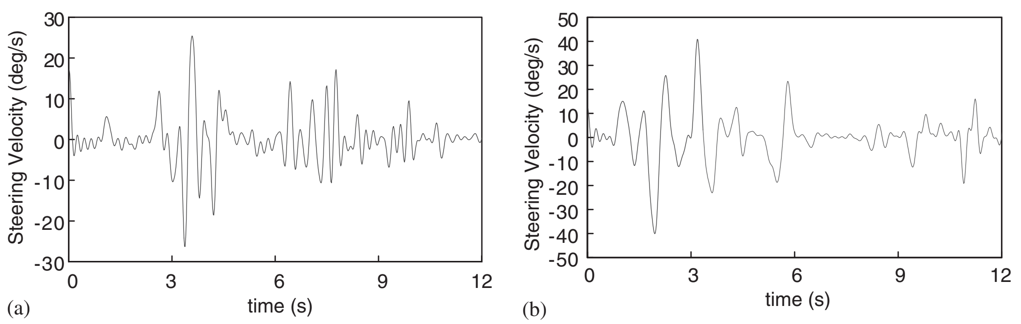

Figure 6. Steering angular velocities of examinees during strong shaking: (a) the JMA Kobe; and (b) El Centro records scaled to $PGA = 4\,\mathrm{m/s^2}$ were used as ground motions.

Experiment 1: Characteristics of examinees' responses to different ground motions

The first experiment aims to evaluate the response characteristics of the examinee to different intensities of ground motions. Ten examinees were divided into two groups. The JMA Kobe records scaled to PGA equal to $2\,\mathrm{m/s^2}$, $4\,\mathrm{m/s^2}$, and $6\,\mathrm{m/s^2}$ were used as ground motions for one group, and the JMA Kobe records scaled to PGA equal to $1\,\mathrm{m/s^2}$ and $4\,\mathrm{m/s^2}$, and the SCT Mexico record scaled to PGA equal to $1\,\mathrm{m/s^2}$ were used as ground motions for

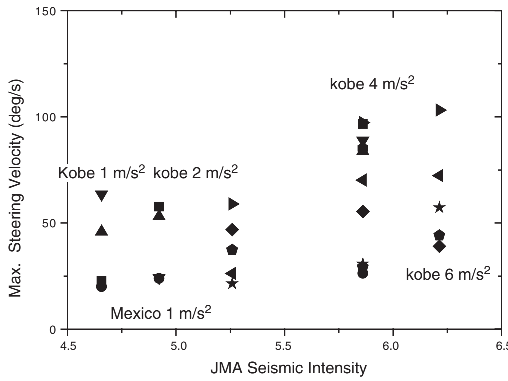

Figure 7. Relationship between the maximum steering velocity and JMA seismic intensity of ground motions.

the other group. Figure 7 shows the relationship between the maximum steering velocity and JMA seismic intensity [10] of ground motions. The result for each examinee is shown by a different symbol. In our previous research [5] it was observed that the absolute response acceleration of a moving vehicle is highly correlated with the JMA seismic intensity and the response acceleration becomes continuously larger as the JMA seismic intensity of ground motion becomes larger. However, one can see (Figure 7) that the reaction of the examinee does not increase continuously, because the human reactions are different depending on each person and seismic motion. It can be seen that the distribution of the maximum steering velocity becomes wider when the JMA seismic intensity becomes almost equal to 6.0. This means that the drivers may feel difficulties when the intensity of ground motion exceeds a certain level. However, a solid conclusion may be drawn by accumulating the data from experiments, which will be conducted in the near future.

Experiment 2: Characteristics of examinees' responses to seismic motion with respect to their driving careers and frequencies

Thirty-three examinees participated in this experiment. Table II shows the distribution of the ages and the driving frequencies of the examinees. The examinees have a broad range of ages and driving experiences, so it is possible to detect differences in reactions to seismic motion between younger and older drivers, and also between frequent drivers, who drive at least a few times a week, and infrequent drivers. The JMA Kobe record and the El Centro record were selected as ground motions (16 examinees for the JMA Kobe and 17 examinees for the El Centro). Both the records were scaled to PGA equal to 4m/s^2. Figure 8 shows the relationships between the maximum steering velocity and the length of time a driver has had a license, and between the maximum steering velocity and the frequency of driving. It is observed that the steering velocity is large for the less-experienced and very-experienced (which means older) drivers (Figure 8(a)). Although the differences from examinee to examinee are large, the mean and standard deviation of the peak values for those who drive a few times a week are smaller than for the other examinees (Figure 8(b)). Hence, it is expected that the less-experienced and older drivers may over-react to seismic motion and they may move out of their running

Table II. Distribution of the age and driving frequency of the examinees.

Age	Seldom or never	A few times a month	A few times a week	Almost everyday	Total
JMA Kobe					
21–30	3 (1)[a]	2	1	0	6 (1)
31–40	1	1	1	0	3
41–50	1 (1)	1	1	1	4 (1)
51–65	1	1	1	0	3
All	6 (2)	5	4	1	16 (2)
El Centro					
21–30	2	4	2 (1)	0	8 (1)
31–40	0	0	3 (1)	0	3 (1)
41–50	0	0	1	0	1
51–65	1	1	3	0	5
All	3	5	9 (2)	0	17 (2)

[a] The numbers in parentheses indicate the number of female examinees.

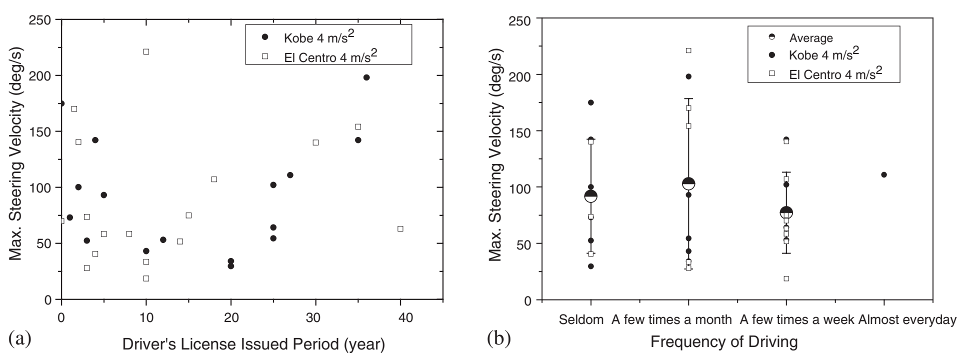

Figure 8. Relationships between: (a) the maximum steering velocity and the length of time a driver has had a license; and (b) the maximum steering velocity and the frequency of driving.

lane. Also, it may be difficult for the drivers who drive less frequently to keep their vehicles stable during strong shaking. These observations on the seismic reaction of drivers are still qualitative and it is not easy to obtain such statistics from many simulator tests. However, these observations may be reasonable because less-experienced and older drivers are apt to cause traffic accidents in ordinary times.

RESPONSE CHARACTERISTICS OF DRIVERS TO SEISMIC MOTION

Response time lag to strong motion

For the 33 examinees, a questionnaire was administered just after the experiment was conducted. Table III shows the prevailing direction of vibration of a vehicle felt by the examinees

Table III. Prevailing direction of vibration of a vehicle felt by examinees during the experiment.

Direction	JMA Kobe	El Centro	Total
Longitudinal	0	2	2
Transverse	8	11	19
Vertical	4	2	6
Unknown	4	2	6
Number of examinees	16	17	33

based on the questionnaire survey. When the JMA Kobe record was used as the ground motion, a half (8/16) of the examinees named the transverse direction of the vehicle. For the El Centro record, about two-thirds (11/17) of the examinees also indicated the transverse direction of the vehicle. In both cases, the transverse direction was named for more frequently than the longitudinal or vertical directions. This finding is very similar to the one obtained from a questionnaire survey conducted by Kawashima *et al.* [4]. Based on this fact, it is expected that there might be a correlation between the drivers' reactions to the seismic motion and the vibration to the transverse direction. In this objective, the response time lag to the ground motion was evaluated using the cross-correlation coefficient [11] between the steering angular acceleration of an examinee and the absolute response acceleration to the transverse direction of a vehicle. In order to obtain the response time lag, the steering angular acceleration was employed instead of the steering velocity because the dimension in terms of time should coincide with the response acceleration. It should be noted that the time lag between the ground motion and the response acceleration of a vehicle is almost equal to 0, and the peak value of cross-correlation is larger than 0.95. The cross-correlation coefficient, $\rho_{xy}(\tau)$, is defined as

$$C_{xy}(\tau) = \int_{-\infty}^{\infty} S_{xy}(\omega) e^{i\omega\tau} \, d\omega \tag{1a}$$

$$\rho_{xy}(\tau) = \frac{C_{xy}(\tau)}{\sigma_x \sigma_y} \tag{1b}$$

where S_{xy} is the cross-spectral density function between the absolute response acceleration to the transverse direction of a vehicle and the steering angular acceleration of an examinee; σ_x and σ_y are the standard deviations of the absolute response acceleration to the transverse direction and the steering angular acceleration, respectively; and C_{xy} and ρ_{xy} are the cross-correlation function and cross-correlation coefficient, respectively.

The cross-correlation coefficient was calculated using the record for 6 seconds, which is the main part of the shaking. Figure 9 shows the typical examples of the calculated cross-correlation coefficients that were obtained from different examinees. From the calculated cross-correlation coefficients, the peak values and their time lags were extracted. Figure 10 shows the relationship between the peak value of the cross-correlation coefficient and the associated time lag. For almost all examinees, the time lag is in the range of 0.2–0.5 seconds. It is observed that the time lag associated with the positive peak value is larger than that of the negative peak value.

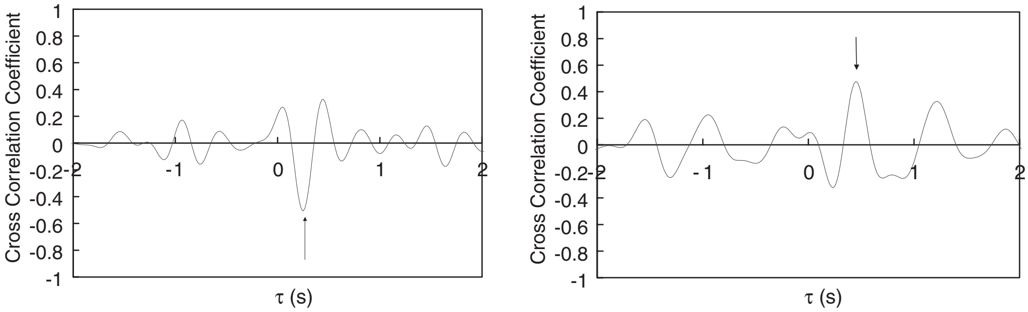

Figure 9. Examples of the cross-correlation coefficient between the steering angular acceleration and the response acceleration of the vehicle. The JMA Kobe record scaled to $PGA = 4\,\mathrm{m/s^2}$ was used as ground motion.

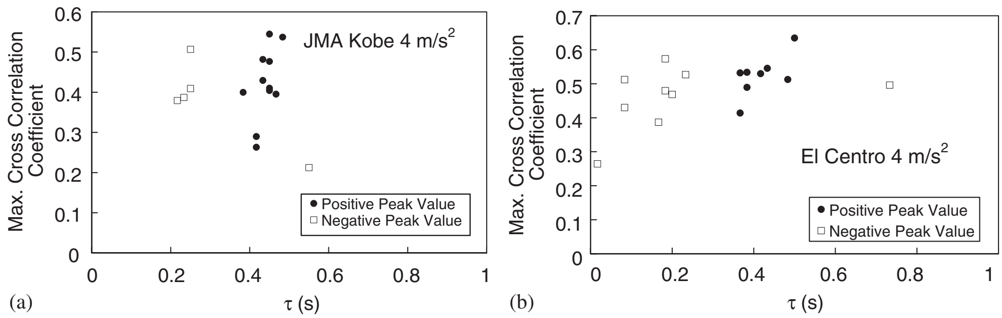

Figure 10. Relationship between the peak value of cross-correlation coefficient and the associated time lag under: (a) the JMA Kobe; and (b) the El Centro records scaled to $PGA = 4\,\mathrm{m/s^2}$.

Note that the positive directions are defined as 'right-to-left' for the absolute transverse acceleration and 'counterclockwise' for the steering angular acceleration. Therefore, the examinees whose peak values of the cross-correlation coefficients are positive have tendencies to turn the steering wheel to the same direction as the ground acceleration. If a driver turns the steering wheel with steering angular acceleration of the same sign as the ground acceleration without time lag, the driver amplifies the seismically induced response of a vehicle, especially for the yaw angular velocity as shown in Figure 11, where the gain of the steering angular acceleration to the ground acceleration was set as 50 deg/m. If a driver turns the steering wheel with steering acceleration of the different sign to the ground acceleration, the driver can decrease the seismically induced yaw angular velocity. But numerical experiments demonstrated that if this gain is set larger, the yaw angular velocity becomes larger than that without steering response even though the steering angular acceleration has a different sign to the ground acceleration. According to the results of the previous research [5], the lateral displacement of a vehicle subjected to the seismic motion is not so large (see bold lines in Figure 12 shown in the next section). Based on these findings, the effective way to keep the vehicle stable during an earthquake motion is to turn the steering wheel slightly and rapidly

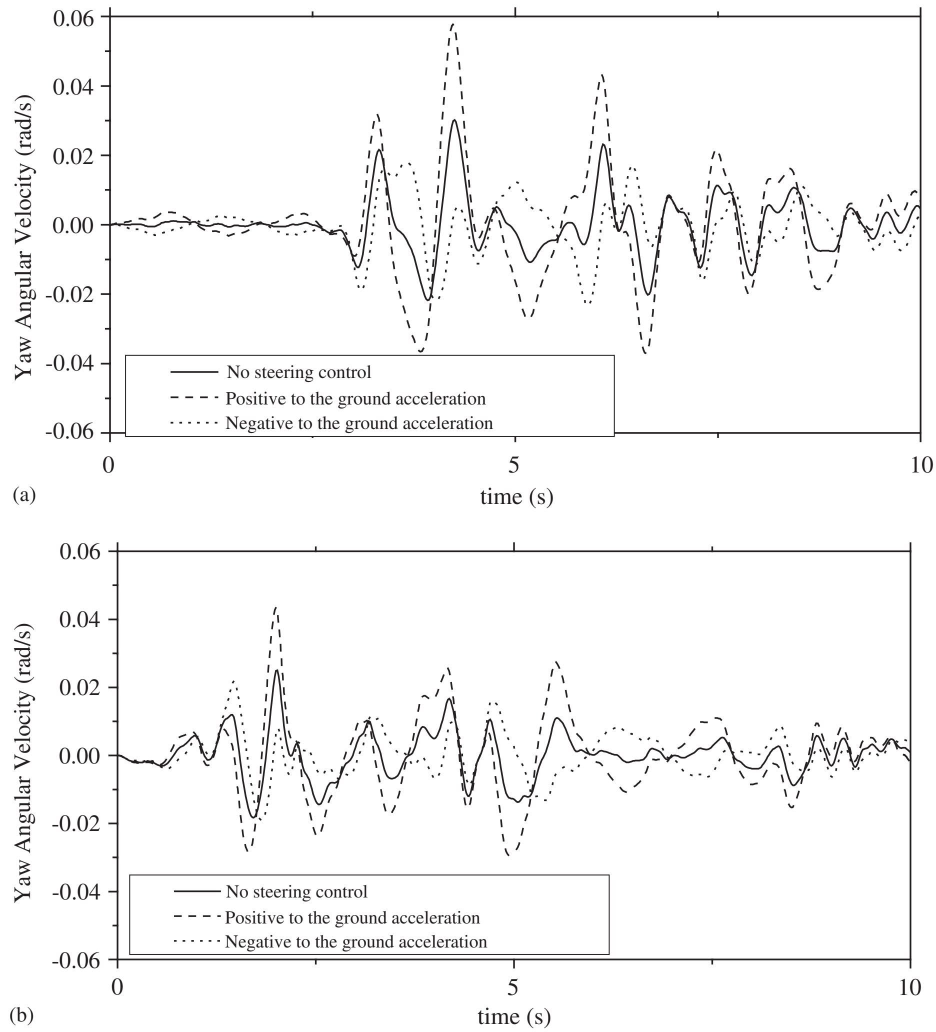

Figure 11. Comparison of the yaw angular velocities for the cases with different steering angular accelerations: (a) the JMA Kobe; and (b) the El Centro records were scaled to $PGA = 4\,\mathrm{m/s^2}$.

to the opposite direction of the ground acceleration, but this cannot be done when the seismic input changes more rapidly than the driver can react.

Running trajectory of a vehicle during an earthquake

The running trajectories for the 33 examinees were calculated as

$$v = v_{\mathrm{seism}} + v_{\mathrm{driver}} \tag{2a}$$

$$\dot{\psi} = \dot{\psi}_{\mathrm{seism}} + \dot{\psi}_{\mathrm{driver}} \tag{2b}$$

$$\dot{Y} = u \sin \psi + v \cos \psi \tag{2c}$$

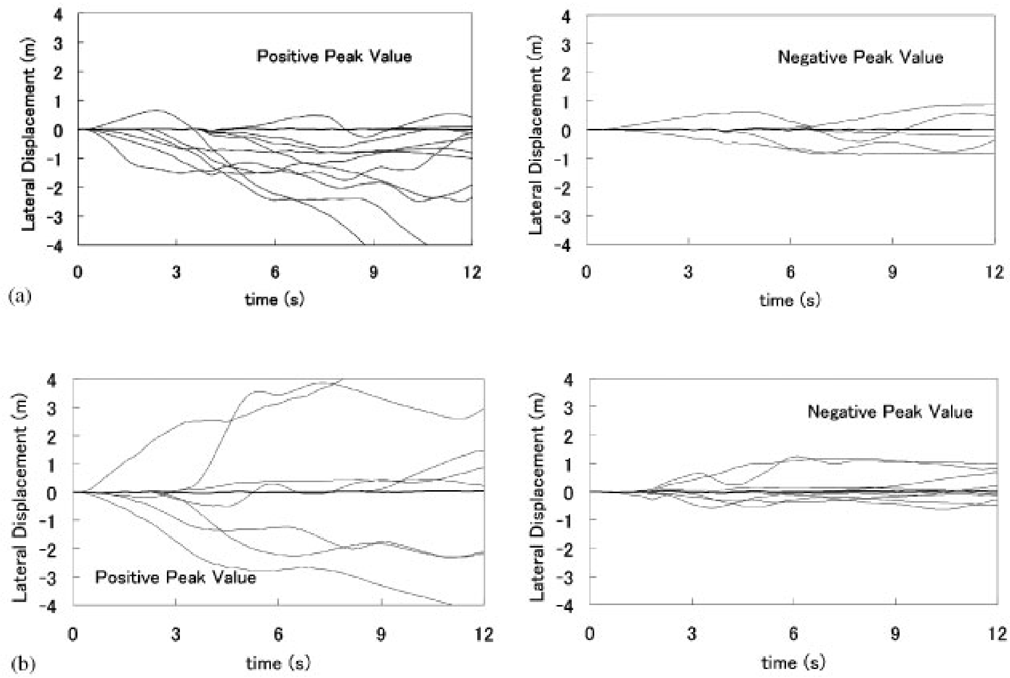

Figure 12. Running trajectory of the vehicle without considering driver's reactions (bold line) and those of the examinees (thin lines) under: (a) the JMA Kobe; and (b) the El Centro records scaled to $PGA = 4\,\mathrm{m/s^2}$.

where u, v and $\dot{\psi}$ are the longitudinal, transverse, and yawing velocities, respectively. $\dot{Y}$ is the relative lateral velocity of the vehicle in the absolute coordinate [5]. The subscript 'seism' represents the relative response to the ground motion, and the subscript 'driver' represents the response of an examinee. For the longitudinal velocity, u_{seism} is so small that u_{driver} was used as u in Equation (2c). Figure 12 shows the running trajectories of the examinees when the JMA Kobe and El Centro records scaled to PGA equal to $4\,\mathrm{m/s^2}$ were used as the ground motion. The results of seismic response analyses of a moving vehicle without considering the driver's reactions [5] were also plotted to provide a standard of comparison. According to the numerical simulations, a vehicle will not shift to the adjacent lane unless the driver over-reacts against strong motion. The experimental results were classified with respect to the peak value of the cross-correlation coefficient. In Japan, the width of a single expressway lane is usually 3.6 m and the width of a vehicle is around 1.7 m. Thus, a vehicle will intrude into the adjacent lane when the course deviation exceeds around 1.0 m. Some of the examinees whose peak values of the cross-correlation coefficients were positive tended to intrude into the adjacent lane when subjected to strong shaking. On the other hand, the course deviations associated with the negative cross-correlation coefficients were not so large as to intrude into the adjacent lane. Similar observations could be found for both ground motions.

There are some numerical models that consider the interaction between the motions of a vehicle and the responses of a driver. In this study, the second-order predictable correction

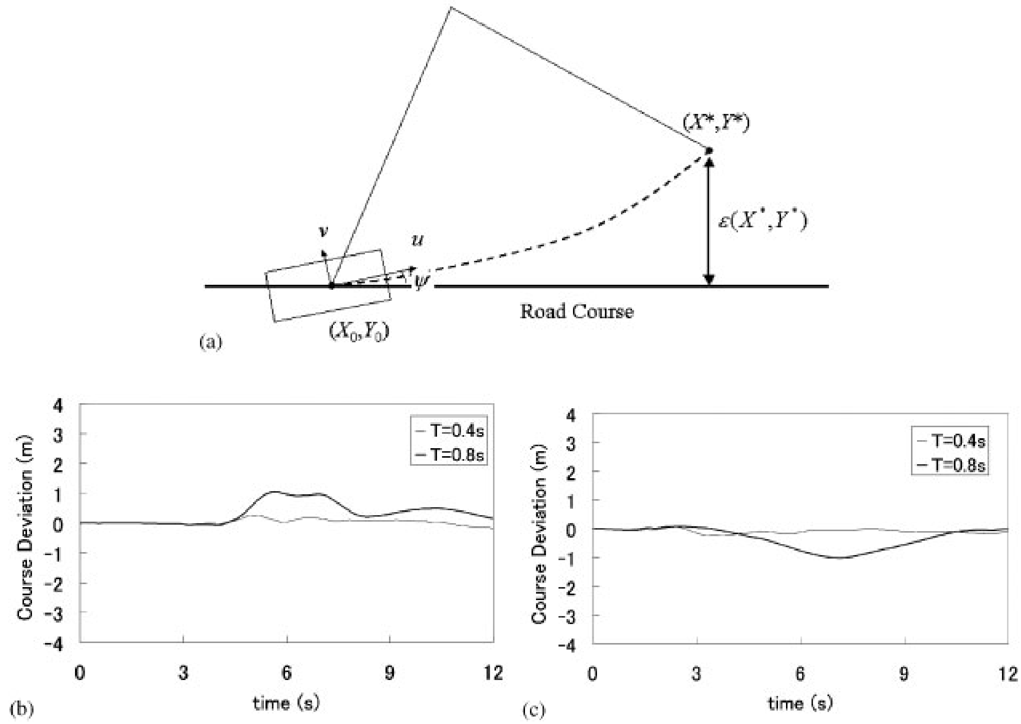

Figure 13. (a) Outline of the second-order predictable correction model; and the calculated running trajectories of the vehicle subjected to; (b) the JMA Kobe record; and (c) the El Centro record, scaled to $PGA = 4\,\mathrm{m/s^2}$.

model proposed by Yoshimoto [12] was used for the numerical simulation of responses of a vehicle during an earthquake including the reactions of a driver. Figure 13(a) 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 of the direction of velocity because they feel the inertial force due to acceleration. Based on this assumption, the position at time t_1 from the present position, (X_0, Y_0), can be predicted as

$$X^* = X_0 + \int_0^{t_1} \{u\cos(\psi + \dot{\psi}t) - v\sin(\psi + \dot{\psi}t)\}\,\mathrm{d}t \tag{3a}$$

$$Y^* = Y_0 + \int_0^{t_1} \{u\sin(\psi + \dot{\psi}t) + v\cos(\psi + \dot{\psi}t)\}\,\mathrm{d}t \tag{3b}$$

where X^* and Y^* are the predicted future position of the longitudinal and transverse components in the absolute coordinate, respectively. Then, the course deviation ε at t_1 can be obtained. It is also assumed that the driver produces a 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

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

Parameter	Definition	Value	Unit
H	The proportional constant for turning steering force	1.8	N/m
t_1	The time for predicting future position	2.9	s
T	The sampling period for turning steering	0.4/0.8	s
I	Mass moment inertia of steering system	11.8	Nms^2/rad
C	The damping coefficient of steering system	882	Nms/rad
K_{st}	The elastic constant of the steering	48.5	kNm/rad
n	The inverse of overall steering ratio	1/15	–
r	The radius of steering wheel	0.2	m

expectation of the time delay for the motion is equivalent to $T/2$ [12]. Based on this assumption, the steering force performed by the driver with time interval T is shown as

$$f = H\varepsilon \tag{4}$$

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

$$In\frac{\mathrm{d}^2A}{\mathrm{d}t^2} + Cn\frac{\mathrm{d}A}{\mathrm{d}t} + K_{st}(nA - \delta_t) = \frac{fr}{n} \tag{5}$$

where I, C, and K_{st} are the mass moment 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 the running velocity of a vehicle; r is the radius of the steering wheel; and A is the steering angle. δ_t is the angle difference between the longitudinal direction and the direction of the front tires, and it is denoted as

$$\delta_t = nA + (SAT_{11} + SAT_{12})/K_{st} \tag{6}$$

where SAT is the Self Aligning Torque [13]. Table IV shows the parameters used for the numerical simulation. It should be noted that other parameters not listed in Table IV are the same as in a previous study [5]. Based on the experimental results (Figure 12), the time lags of the drivers were estimated to be 0.2 s and 0.4 s. Then, T was set as 0.4 s and 0.8 s. Figures 13(b) and (c) show the calculated running trajectories subjected to the JMA Kobe and El Centro records scaled to PGA equal to 4 m/s^2. Although the other parameters are set as the same for both cases, except for T, the calculated running trajectory with larger T shows a larger course deviation. This means that a driver who has a larger response time lag will have a higher likelihood of intruding into the adjacent lane, which can also be seen in Figure 12. Note that the driver whose time lag is large has the tendency to have a positive peak value of the cross-correlation coefficient.

Figure 14(a) shows the relationship between the peak value of the cross-correlation coefficient and the maximum steering angular velocity. The examinees who have positive peak values of the cross-correlation coefficients show a larger steering angular velocity than those whose peak values are negative. This might be another reason why the examinees who have a positive peak value of the cross-correlation coefficient are associated with the larger course deviations. Conversely, the examinees whose peak value of the cross-correlation coefficient

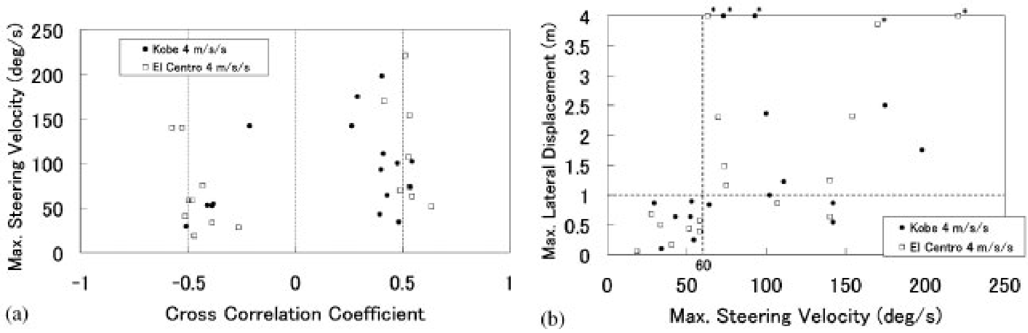

Figure 14. Relationships between: (a) the peak value of cross-correlation coefficient and maximum steering velocity; and (b) the maximum lateral displacement of the moving vehicle and the maximum steering velocity. (The points marked with $*$ in part (b) are the results from the examinees who moved to the adjacent lane during an earthquake.)

is negative could keep the vehicle stable during an earthquake motion because they turn the steering wheel slightly and rapidly to compensate for the ground acceleration. Although the relationships between the peak value of the cross-correlation coefficient and the age of the examinees, or the driving frequency of the examinees, were investigated, no specific tendency was found. The causes that a driver could turn the steering wheel to the ‘right’ direction may depend on the motor nerve of the driver rather than the driving career or frequency.

Based on these findings, it can be said that owing to the two main factors, the response time lag and over turning of the steering wheel, the drivers subjected to ground excitation move out of their running lane. Thus, traffic accidents may occur during a strong earthquake shaking if an expressway has heavy traffic.

Figure 14(b) shows the relationship between the maximum steering velocity and the maximum lateral displacement of the vehicle subjected to strong motion. According to the figure, none of the examinees whose maximum steering velocity was smaller than 60 deg/s intruded into the adjacent lane (which means the maximum lateral displacement was smaller than 1.0 m). Based on the results shown in Figures 7 and 14(b), it is thought that a ground motion will not affect the moving vehicle so much when the JMA seismic intensity is equal to or smaller than around 5.0.

CONCLUSION

In this study, simulator experiments on driving a vehicle during an earthquake motion were carried out to investigate the responses of the drivers under strong seismic shaking. Before conducting the experiments, the motion sensitivities of the driving simulator were investigated. Although self-vibration of the driving simulator was seen in the frequency range of 7–8 Hz, this has a minimal effect when the response acceleration of the ground motion lacks a large spectral amplitude in the high frequency range.

Considering the effects of the self-vibration, the JMA Kobe, El Centro, and SCT Mexico records were used as the ground motion. According to the experiments with respect to different intensities of ground motion, the reaction of the examinee does not increase continuously as the intensity of ground motion becomes larger. It seems that the distribution of the maximum steering velocity becomes wider when the JMA seismic intensity becomes almost equal to 6.0. Thus, drivers might feel some difficulties when the intensity of ground motion exceeds a certain level. However, future research is needed to confirm this conclusion. In order to clarify the response characteristics of examinees to seismic motion with respect to their driving careers and frequencies, 33 examinees were employed in driving simulator experiments. The results suggest that steering velocity is larger for less-experienced drivers and very-experienced drivers (who have been issued with driver's licenses for more than about thirty years, i.e. senior drivers).

The running trajectories during earthquake shaking were calculated for the 33 examinees. The results showed that examinees who have a larger response time lag to the strong shaking show larger course deviations. A similar tendency is also observed in the numerical simulation considering the interaction between the motions of a vehicle and the reactions of a driver using a second-order predictable correction model. In addition, these examinees show larger steering velocities compared to the other examinees. These response characteristics cause an intrusion into the adjacent lane, which could cause a traffic accident if there is heavy traffic. The most effective way to keep the vehicle stable during strong shaking is to avoid over-reactions due to abnormal vibrations of the vehicle. If drivers do not turn the steering wheel excessively, the running vehicle will not show a very large course deviation.

A future study will investigate the effectiveness of giving drivers advance warning of seismic shaking. Such warnings should be studied because the JMA plans to establish a system to issue 'Nowcast Earthquake Information' [14], which will include the estimated arrival time of the main shaking part of seismic waves calculated using the difference of the P-wave and S-wave velocities. Using both the Intelligent Transportation System (ITS) and the Nowcast Earthquake Information, it will be possible to send an alert that makes drivers prepare for seismic shaking, or even controls vehicles automatically. An important topic for this research would be to determine what is the minimum amount of forewarning that would be needed for drivers to take effective corrective action.

ACKNOWLEDGEMENT

This research was partially supported by the Sasagawa Scientific Research Grant from the Japan Science Society.

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