ICOSSAR 2005, G. Augusti, G.I. Schuëller, M. Ciampoli (eds)

New aspects of seismic safety of expressways focusing on the behavior of automobile drivers

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Keywords: expressways network, seismic motion, vehicle model, driving simulator, moving stability

ABSTRACT: After the 1995 Kobe earthquake, the expressway structures in Japan have been retrofitted and they will not be seriously damaged under a certain level of strong earthquake motion. However, the stability of a moving vehicle has not been investigated yet. For a further safety promotion of the expressway networks, it is important to understand the drivers' reactions to seismic motion. To achieve this objective, a vehicle model with a six-degree-of-freedom system is employed and its responses under seismic motions are obtained for five sets of actual ground motion records. Furthermore, some series of virtual tests using the driving simulator are conducted to reveal the response characteristics of the drivers during strong shaking. Based on the results, the early warning of seismic motion will be possible to contribute the further safety promotion of the expressway networks during an earthquake.

1 INTRODUCTION

As the demand for highway traffic increases, safety requirements for highways significantly increase even at the time of an earthquake. Recent strong earthquakes, notably, the 1989 Loma Prieta, the 1994 Northridge, and the 1995 Kobe earthquakes, have caused heavy damages to expressway structures. Hence, the countermeasures against strong earthquakes became one of the most important issues of highway authorities (Yamazaki 2001). After the 1995 Kobe earthquake, the new seismometer networks have been developed along the expressways in Japan, and the regulation of traffic is to be conducted using the earthquake records from these instruments. However, the current regulations need to be examined since the major structural damages that affect safety driving on an expressway are seldom found under the current regulation level of seismic motions (Yamazaki *et al*. 2000).

For the efficient traffic control of expressways immediately after an earthquake, the effect of seismic motion on automobile driving should also be considered along with the structural damages. Many of the drivers who have experienced an earthquake on the expressways reported that they felt seismically induced vibrations, especially to the transverse direction (Kawashima *et al*. 1989). From a questionnaire survey, it was found that some drivers mistakenly recognized the earthquake as a blowout of tire, and they could not control the steering wheel properly due to abnormal vibration. From the survey, it was also found that the drivers feel difficulty in controlling their vehicles and they may make an accident due to strong shaking. Hence, for a further safety promotion of the expressway networks, it is important to evaluate the drivers' reactions under seismic motion.

To achieve this objective, the vehicle model with a six-degree-of-freedom system is employed and its responses under seismic motions are obtained for five sets of actual ground motion records. The interactions between the seismic response of the expressway structure and that of the moving vehicle are also discussed comparing with the vehicle responses under free field earthquake motions. In addition, some series of virtual tests using the driving simulator are conducted to reveal the response characteristics of the drivers during strong shaking.

2 QUESTIONNAIRE SURVEY ON THE EFFECT OF SEISMIC MOTION TO EXPRESSWAY DRIVERS

Japan Highway Public Corporation (JH) has conducted the questionnaire survey for expressway drivers in the 2003 Sanriku-Minami earthquake, which occurred on May 26, 2003. Based on the questionnaire survey, the response characteristics of drivers subjected to strong shaking are roughly realized.

First, the distribution of Japan Meteorological Agency (JMA) seismic intensity is estimated using

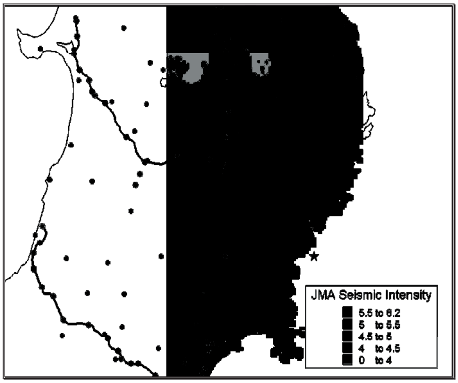


Figure 1. Estimated distribution of JMA seismic intensity by Kriging technique.

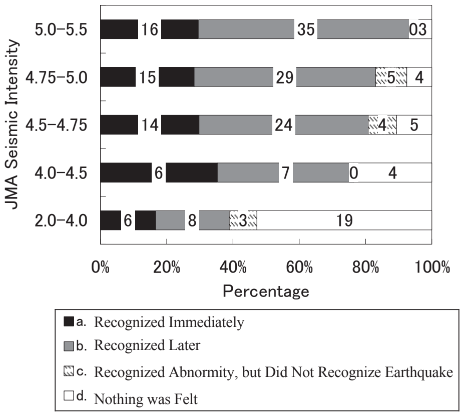


Figure 2. Drivers' degree of recognition of earthquake occurrence with respect to the JMA seismic intensity.

132 seismic records at K-NET stations, which were deployed by National Research Institute for Earth Science and Disaster Prevention, and 52 seismic records at JH stations, which were deployed by JH. Kriging technique (Cressie 1993), a method of stochastic interpolation, is employed to estimate the spatial distribution of JMA seismic intensity (Shabestari & Yamazaki 2001).

Figure 1 shows the estimated distribution of JMA seismic intensity (Maruyama & Yamazaki 2005). The results of questionnaire survey conducted by JH are compared with the estimated JMA seismic intensity. Figure 2 shows the relationship between the estimated JMA seismic intensity and the degree of recognition of earthquake occurrence. As the JMA seismic intensity becomes larger, more drivers recognized the earthquake occurrence. Only 40 % of drivers were aware of the earthquake in the areas where the JMA seismic intensity is smaller than 4.0. On the contrary, more than 80 % of drivers recognized the earthquake in the areas where the JMA

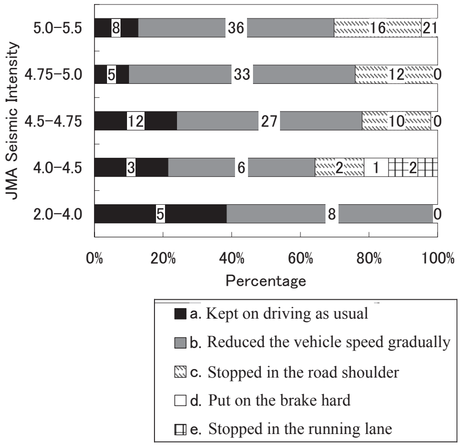


Figure 3. Relationship between the JMA seismic intensity and the responses of drivers after the recognition of earthquake.

seismic intensity is larger than or equal to 4.5. Figure 3 shows the relationship between the JMA seismic intensity and the behaviors of drivers after recognizing the earthquake. About 40 % of drivers in the area where the JMA seismic intensity is smaller than 4.0 kept on driving as usual even though they recognized the earthquake occurrence. As the JMA seismic intensity becomes larger, fewer drivers kept on going. Only 10 % of drivers kept on driving if the JMA seismic intensity was larger than or equal to 4.75.

This finding suggests that the strong ground motion will affect safe and stable driving. In this regard, it is important to reveal the effects of seismic motion to moving vehicles quantitatively.

3 SEISMIC RESPONSE ANALYSIS OF A MOVING VEHICLE

3.1 *Vehicle model*

A vehicle model with a six-degree-of-freedom system is made as shown in Fig. 4. Three axes are set on the center of gravity (c.g.) of a vehicle. The *x*-axis is the longitudinal direction, the *y*-axis is the transverse direction, and the *z*-axis is the vertical direction of the vehicle. The equations of motion of the vehicle to the longitudinal and transverse directions including the effect of seismic motion are defined as

$$m\left(\dot{u} - vr + \ddot{x}\cos\psi + \ddot{y}\sin\psi\right) = \sum_i \sum_j \left(F_{xij}\cos\delta_{tij} - F_{yij}\sin\delta_{tij}\right) \tag{1a}$$

$$m(\dot{v}+ur-\ddot{x}\sin\psi+\ddot{y}\cos\psi)=\sum_i\sum_j\left(F_{xij}\sin\delta_{tij}+F_{yij}\cos\delta_{tij}\right) \quad (1b)$$

where $\ddot{x}$ and $\ddot{y}$ are the ground accelerations to the longitudinal and transverse directions of the vehicle, respectively. u and v are the velocities in the x and y directions, respectively, r is the angular velocity of yawing, and δ is the angle difference between the x-direction and the direction of each tire. F_x and F_y are the longitudinal and transverse forces of each tire, respectively. These forces are calculated by a physical tire model (Bakker *et al*. 1989). The index i represents the front or rear wheel and the index j represents the left or right wheel. m (= m_1+m_2) is the mass of the vehicle.

According to this model, the equation of motion to the vertical direction is described as

$$m_1(\ddot{\zeta}_1+\ddot{z}_{in})+c_1\dot{\zeta}_1+c_2(\dot{\zeta}_1-\dot{\zeta}_2)+k_1\zeta_1+k_2(\zeta_1-\zeta_2)=0 \quad (2a)$$

$$m_2(\ddot{\zeta}_2+\ddot{z}_{in})+c_2(\dot{\zeta}_2-\dot{\zeta}_1)+k_2(\zeta_2-\zeta_1)=0 \quad (2b)$$

where z_{in} is the vertical displacement of the ground. ζ_1 ($=z_1-z_{in}$) and ζ_2 ($=z_2-z_{in}$) are the relative vertical displacements of m_1 and m_2, respectively.

Three kinds of rotational motions, which are pitching motion, θ, rolling motion, ϕ, and yawing motion, ψ, are calculated following our previous research (Maruyama & Yamazaki 2002).

A seismic response analysis is performed using five actual earthquake records. Figure 5 shows the relationship between the peak ground acceleration (PGA) and maximum absolute response acceleration (transverse component) and the relationship between the JMA seismic intensity and maximum absolute response acceleration. In the figure, the variation is seen from event to event with respect to the PGA, however, the variation is not seen with respect to the JMA seismic intensity. The JMA seismic intensity is calculated through a frequency filtering of a three-component record (Shabestari & Yamazaki 2001). This process has the similarity with the response characteristics of the vehicle model used in this study (Maruyama & Yamazaki 2002).

3.2 *Effect of structural response to the moving vehicle*

Metropolitan Expressway Public Corporation (MEX) owns expressway networks with the total length of 281.0 km (as of 2003). The expressway networks consist of several types of structures, such as surface earthwork, tunnel, semi underground structure and so on. The elevated sections are common in the Metropolitan Expressway, and they cover more than 80 % of the total length of the expressway networks (MEX 2004). Therefore, the effects of structural seismic responses on the moving stability

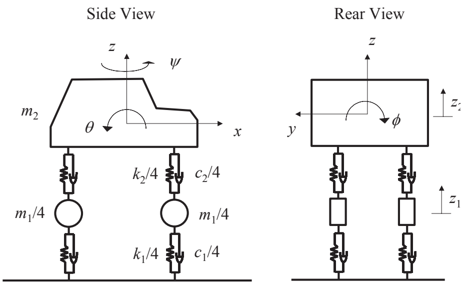
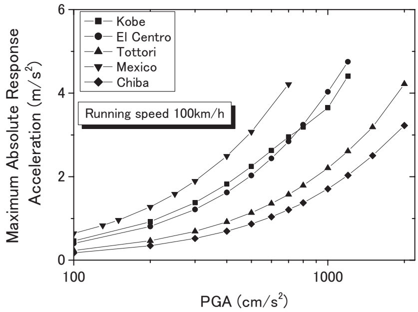
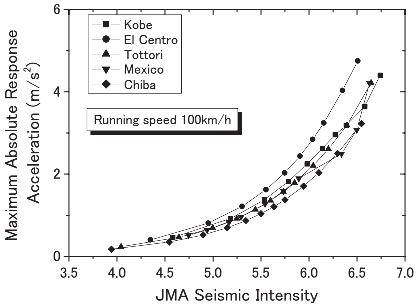


Figure 4. Vehicle model with a six-degree-of-freedom system used in this study.



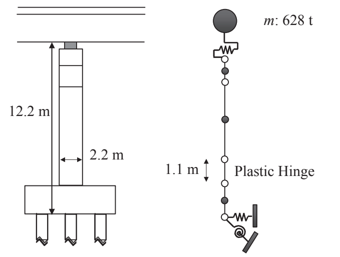
(a) PGA



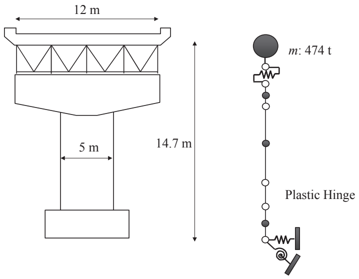
(b) JMA seismic intensity

Figure 5. Relationship between the maximum absolute response acceleration of the vehicle and the peak ground acceleration to the transverse direction and the relationship between the maximum absolute response acceleration of the vehicle and the JMA seismic intensity of the ground motion.

of an automobile should be considered. A RC bridge structure with five spans and the total length of 200 m is used as a target bridge in this study. The bridge pier is modeled as shown in Fig. 6. A rubber bearing

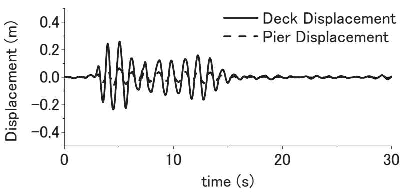


(a) Longitudinal component

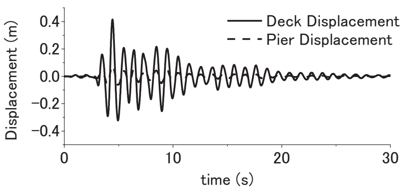


(b) Transverse component

Figure 6. Physical model of the bridge pier used in this study.



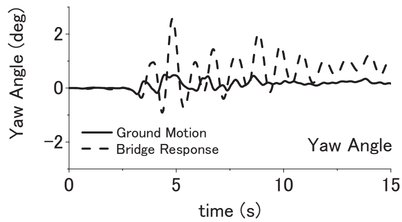
(a) Longitudinal component (EW component)



(b) Transverse component (NS component)

Figure 7. Seismic response of the target bridge pier under JMA Kobe record.

is used as the isolation device in this bridge pier. The predominant period of this bridge pier is 1.19 s for the longitudinal direction, and 1.02 s for the trans-



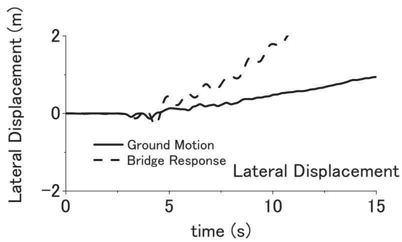
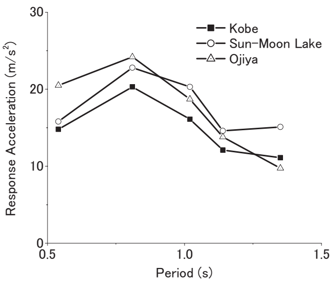


Figure 8. Comparisons between responses of the vehicle under the ground motion and those under the response of bridge pier. (Input ground motion is JMA Kobe record.)

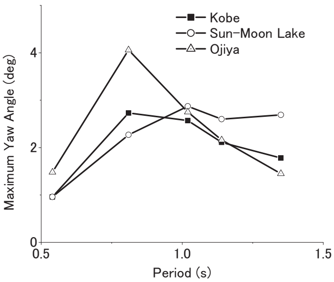
verse direction. This bridge pier is designed according to Japanese seismic design code (Japan Road Association 1998).

The response accelerations of the bridge pier are applied to the vehicle model to conduct the seismic response analysis. For the vertical component, the ground motion record is used as input acceleration. The input ground motion is JMA Kobe record in the 1995 Kobe earthquake, and the moving speed of the vehicle is set to be 100 km/h. Figure 7 shows the response acceleration and displacement of the bridge pier. In the figure, the maximum relative response displacement of the bridge deck is about 0.4 m because the rubber bearing is used as the isolation devise. Figure 8 shows the yaw angle and lateral displacement of the vehicle under the ground motion and those under the response of the bridge pier. The yaw angle under the structural response is larger than that under the ground motion. The vehicle rotates heavily and the maximum yaw angle is about 3 deg under the structural response. Therefore, the moving vehicle under the response of bridge pier shows larger lateral displacement than that under ground motion.

Figure 9 (a) shows the relationship between the predominant period of the bridge pier and the maximum response acceleration. The predominant period of the bridge pier is determined by changing the stiffness of the rubber bearing. Three sets of actual ground motion records are used for this numerical analysis. If the predominant period of the bridge pier is set to be 0.81 s, the maximum response accelera-



(a) Response acceleration of the bridge pier



(b) Yaw angle of the moving vehicle

Figure 9. Relationships between the maximum response acceleration and the predominant period of the bridge pier (transverse component) and between the maximum yaw angle of the moving vehicle and the predominant period of bridge pier.

tion shows the largest value for the three ground motions. Figure 9 (b) shows the relationship between the yaw angle and the predominant period of the bridge pier. When the JMA Kobe record and the K-NET Ojiya record during the 2004 Niigata-ken Chuetsu earthquake are used as ground motions, the maximum yaw angles show the largest values in the case that the predominant period of the bridge pier is 0.81 s. On the other hand, the maximum yaw angle under the Sun-Moon Lake record during the 1999 Chi-Chi earthquake shows the largest value when the predominant period of the bridge pier is 1.02 s.

The response characteristics obtained in this study might be dependent on the ductility of the bridge structure and the frequency characteristics of the input ground motions. To draw a solid conclusion, further investigations are needed on this issue.

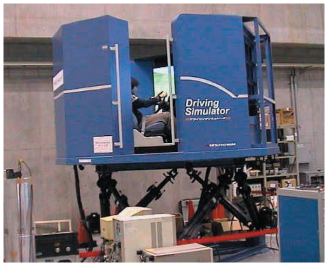
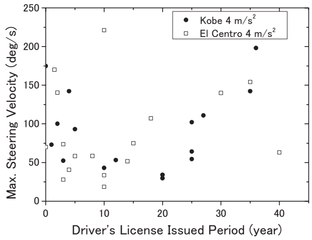
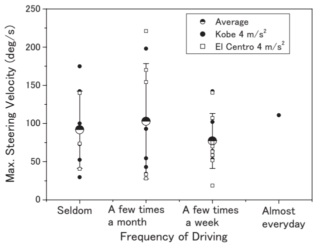


Figure 10. Driving simulator used in this study.



(a) Driver's license issued period



(b) Frequency of driving

Figure 11. Relationships between the maximum steering velocity and the driver's license issued period and between the maximum steering velocity and the frequency of driving.

4 DRIVING SIMULATOR EXPERIMENT

4.1 *Response characteristics of drivers during an earthquake*

In the seismic response analysis conducted in this study, the response characteristics of the moving vehicle are revealed. However, the reactions of a driver to strong shaking are not considered in this analysis. In this section, some series of virtual driving tests using a driving simulator are conducted to investi-

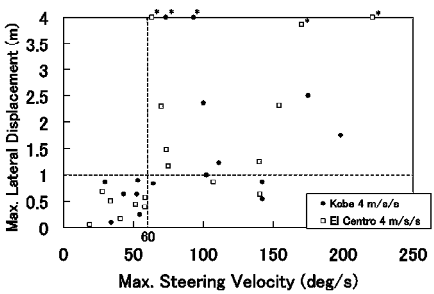


Figure 12. Relationship between the maximum lateral displacement of the moving vehicle and the maximum steering velocity. (The points with * are the results from the examinees who moved to the adjacent lane during an earthquake.)

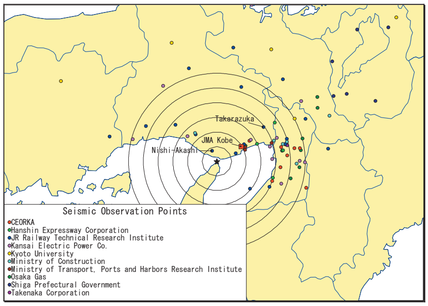


Figure 13. Locations of seismic observation points and epicenter in the 1995 Kobe earthquake. (The distance between each adjacent circle is 10 km.)

gate the response characteristics of drivers subjected to seismic motion.

Figure 10 shows the driving simulator used in this study. 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. The main program of the host computer was modified in order to apply the absolute response displacement due to seismic ground motion of a moving vehicle to the actuator system (Maruyama & Yamazaki 2004).

Thirty-three (33) examinees participated in the experiment. 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 aged drivers, and also between frequent drivers, who drive at least a few times a week, and non-frequent ones. 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 4 m/s^2.

Figure 11 shows the relationships between the maximum steering velocity and the driver's license issued period, 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 aged) drivers (Figure 11(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 the other examinees (Figure 11(b)).

Figure 12 shows the relationship between the maximum steering velocity and the maximum lateral displacement of the vehicle subjected to strong motion. Considering the width of a single lane of the expressway (3.6 m) and that of a vehicle (1.7 m), a vehicle will intrude into the adjacent lane when the lateral displacement exceeds around 1.0 m. According to the figure, the large lateral displacement is associated with the large steering velocity. The results in Fig. 11 and Fig. 12 suggest that the less-experienced and aged drivers may overreact to seismic motion and they may protrude the running 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 are common to the traffic accidents at ordinary time.

4.2 *Effect of early warning of seismic motion to expressway drivers*

JMA plans to provide the early earthquake warning, which is called "Nowcast Earthquake Information" (Doi 2002). Nowcast Earthquake Information contains the arrival time of S-wave and the magnitude of seismic motion, which are estimated by the P-wave detection at a seismic observation station near the hypocenter. It is expected that an emergency response and a countermeasure against tsunami disaster are performed rapidly using this information. If Nowcast Earthquake Information is applied to the expressway network, it will be helpful to avoid traffic accidents, for example, multiple smashups in the collapsed sections of an expressway.

Nowcast Earthquake Information is assumed based on the seismic records and the locations of accelerometers in the 1995 Hyogo-ken Nanbu (Kobe) earthquake (Fig. 13). The nearest seismic observation station from the epicenter is Japan Railway (JR) Nishi-Akashi station, whose epicentral distance is about 8 km. JR Takarazuka station, where the vehicle is assumed to be moving, is away from about 39.5 km from the epicenter. The average P-wave and S-wave velocities were set to be 5.65 km/s and 3.51 km/s, respectively (Tong & Yamazaki 1995).

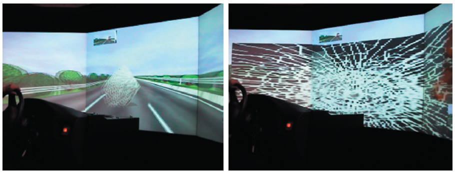


Figure 14. Example of the driving simulator experiment to avoid the obstacle during an earthquake without early warning of seismic motion. (crashed in the obstacle.)

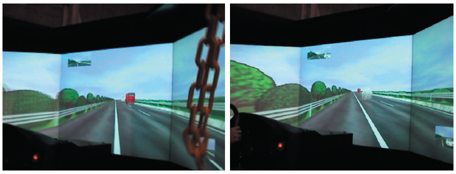


Figure 15. Example of the driving simulator experiment to avoid the obstacle during an earthquake with early warning of seismic motion. (stopped in the road shoulder.)

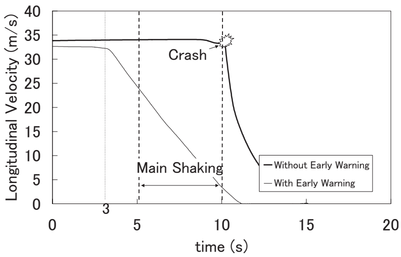


Figure 16. Comparison of the moving speeds of the examinees with/without early warning of seismic motion.

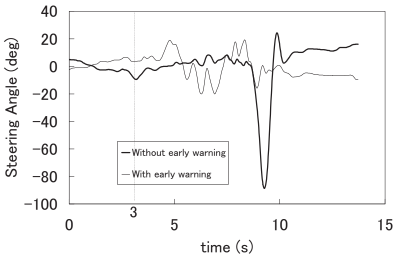


Figure 17. Comparison of the steering angles of the examinees with/without early warning of seismic motion.

At JR Nishi-Akashi station, the P-wave is detected in about 1.4 s after the occurrence of the earthquake. It takes 4 s to issue the 0-th Nowcast Information after the P-wave detection. At JR Takarazuka station, the S-wave will arrive in about 11.3 s after the earthquake occurrence. Therefore, the allowance time after receiving the 0th order Nowcast Information is 5.9 s. Taking the time to start the system of early warning for the expressway network into consideration, it is assumed that the earthquake early warning is given to the drivers 5 s ahead of the arrival of S-wave.

Based on the assumption described above, a driving simulator experiment is conducted to investigate the effects of early warning of seismic motion. The examinees were instructed to drive at the speed of 120 km/h and in the left lane. The seismic motion recorded at JR Takarazuka station during the 1995 Kobe earthquake was used as the ground motion in the experiment. Twenty-two (22) examinees participated in the experiment. Three examinees were in the 30s, three were in the 40s, and the others were in the 20s. A big stone was inserted 50 m ahead of the examinee as an obstacle in the driving simulator experiment. This is because there may occur some disorders in front of the vehicle that affects safety driving, such as, cracks and depressions of road surface, freightage fallen from cargo trucks, and so on. It is not denied that multiple smashups of moving vehicles will be caused because of these kinds of obstacles. The 22 examinees were divided into two groups. The early warning of seismic motion was given to one group, and it was not given to the other group. The message tells the drivers that an earthquake motion is coming, and thus reduce speed and stop the vehicle in the road shoulder. It takes three seconds to speak the whole message in Japanese.

Figure 14 shows the example of the experiment without early warning of seismic motion. Figure 15 shows the example of the experiment when the early warning was given. The examinee without early warning could not avoid crashing to the obstacle. The examinee, who received the early warning, did not crash into the obstacle because the message instructed to stop the vehicle in the road shoulder.

Figure 16 shows the moving speeds of the two examinees shown in Fig. 14 and Fig. 15. The examinee who received the early warning reduced the moving speed because the message requested to stop in the road shoulder. On the contrary, the examinee without early warning did not put on the brake, then kept on driving at the constant speed. Figure 17 shows the steering angles of the two examinees. To escape from the obstacle, the examinee without early warning had only to turn the steering wheel larger than the examinee with early warning.

As a whole, the 9 examinees out of 11 could not avoid traffic accidents because of the obstacle without early warning of seismic motion. On the other hand, the 9 examinees could avoid crashing into the obstacle when the early warning was given to them. Based on the results, although more detailed investigations are necessary to make a solid conclusion, the early warning will be possible to contribute the further safety promotion of the expressways network during an earthquake.

5 CONCLUSIONS

As a new aspect for a further safety promotion of the expressway network during an earthquake, the moving stability of an automobile and driver's reaction to seismic motion are discussed based on the numerical simulation and driving simulator experiment.

According to the results of the questionnaire survey to drivers who experienced an earthquake during driving, seismic motion affects safe and stable driving. If the JMA seismic intensity is larger than 4.5, about 20% of drivers stopped their vehicles in the road shoulder because they felt abnormality. The results of driving simulator experiments suggest that less-experienced drivers and very-experienced drivers, who are issued the driver's licenses for more than about thirty years (which means senior drivers), have the tendency to overreact to the seismic motion, and they may intrude into the adjacent lane because of strong shaking. When the vehicle is moving on the expressway structure, the yaw angle of the vehicle may become larger than that of the vehicle moving on the ground. In this case, the drivers feel more difficulty in controlling their vehicles.

The effects of early warning of seismic motion is also investigated through a series of driving simulator experiments. Although more detailed investigations are necessary to make a solid conclusion, the early warning will be possible to contribute the further safety promotion of the expressways network during an earthquake. The early warning of seismic motion will be more effective if it works together with the Intelligent Transportation System (ITS), especially in the way to send the early warning to the expressway drivers because many drivers can get the earthquake information at the same time.

ACKNOWLEDGEMENT

The authors appreciate Japan Highway Public Corporation for providing the data of the questionnaire survey.

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