Journal of Earthquake and Tsunami, Vol. 3, No. 4 (2009) 261–272

EFFECTS OF EARTHQUAKE EARLY WARNING TO EXPRESSWAY DRIVERS BASED ON DRIVING SIMULATOR EXPERIMENTS

YOSHIHISA MARUYAMA, MASATO SAKAYA and FUMIO YAMAZAKI
Department of Urban Environment Systems, Chiba University
1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

To reduce casualties and troubles due to earthquakes, Japan Meteorological Agency (JMA) introduced earthquake early warning (EEW) to general public on October 1, 2007. However, the possibility that EEW induces traffic accidents exists because EEW through car radio may not be transmitted to all the expressway drivers. Hence, the effects of EEW were investigated based on driving simulator experiments. Two kinds of experiments were performed in this study. First, single driving simulator was employed to reveal the effects of EEW on expressways. The reactions of drivers with/without warning are compared in avoiding an obstacle induced by seismic motion. Second, three synchronized driving simulators, simulating three cars running together on an expressway, were employed. When EEW was transmitted to only one car, some drivers reduced speed suddenly, and accidents occurred in 2 cases out of 14 tests. These experiments show the necessity of public education how to react an EEW on expressways. Turning on the hazard lights after receiving an EEW and then reducing speed gradually is suggested to avoid traffic accidents.

1. Introduction

Utilization of the time gap between the arrivals of P-wave and S-wave has recently been paid attention in some earthquake prone regions. In Mexico City, Seismic Alert System (SAS) has already been in an actual use to send the early earthquake warning [Lee and Espinosa-Aranda, 2002]. Taiwan Rapid Earthquake Information Release System (TREIRS) has been operated since March 3, 1996 [Wu *et al.*, 2002]. Allen and Kanamori [2003] discussed the potential for earthquake early warning in southern California.

The Japan Meteorological Agency (JMA) is observing seismicity based on the network of seismometers throughout Japan. They report the JMA seismic intensity [Shabestari and Yamazaki, 2001], tsunami information, the position of the hypocenter and the JMA magnitude in about two minutes just after the occurrence of an earthquake. The JMA also plans to provide the earthquake early warning (EEW), which contains the arrival time of S-wave and the intensity of seismic motion estimated from the P-wave detected near the hypocenter [Doi, 2002]. It is expected that the preparations for strong shaking and tsunami can start based on an EEW and thus, emergency responses can be performed rapidly and efficiently.

The EEW has been under operation in Japan on a trial basis since August 2006. The EEW is transmitted to construction sites, railways, factories and so on, where the EEW is utilized properly without confusions. Based on the results of trial operations, the JMA has started to broadcast the EEW to general public through radio and TV since

Fig. 1. Driving simulator used in the experiment in avoiding an obstacle under earthquake early warning.

October 1, 2007 [JMA 2007]. On the other hand, it is pointed out that some troubles may be caused when the EEW is issued to the general public. The possibility that EEW causes traffic accidents exists because the EEW through car radio and TV may not be transmitted to all the expressway drivers.

In this study, a series of driving simulator experiments are conducted to investigate the effects of earthquake early warning to drivers on the expressway. First, the reactions of drivers and the responses to an obstacle appearing ahead of drivers with/without early warning are compared using single driving simulator. Second, the effects of EEW were investigated using three synchronized driving simulators, simulating three cars running together on an expressway. The interaction among vehicles running together on an expressway can be considered in this experiment. The reactions of drivers are observed under various receiving conditions of EEW and the effects of EEW to expressway drivers are investigated.

2. Experiment using Single Driving Simulator

2.1. Outline of the experiment

Figure 1 shows the driving simulator used in the experiment. This driving simulator was developed by Mitsubishi Precision Co., Ltd. A scenario expressway 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. Originally, the vibrations of a moving vehicle are modeled in the driving simulator. 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 and Yamazaki, 2004].

The EEW was simulated based on the seismic records and the locations of accelerometers in the 1995 Hyogo-ken Nanbu (Kobe) earthquake (Fig. 2). The nearest seismic observation station from the epicenter is Japan Railway (JR) Nishi-Akashi station. The epicentral distance is about 8 km. JR Takarazuka station, where the vehicle is assumed to be moving, is located 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 and Yamazaki, 1995].

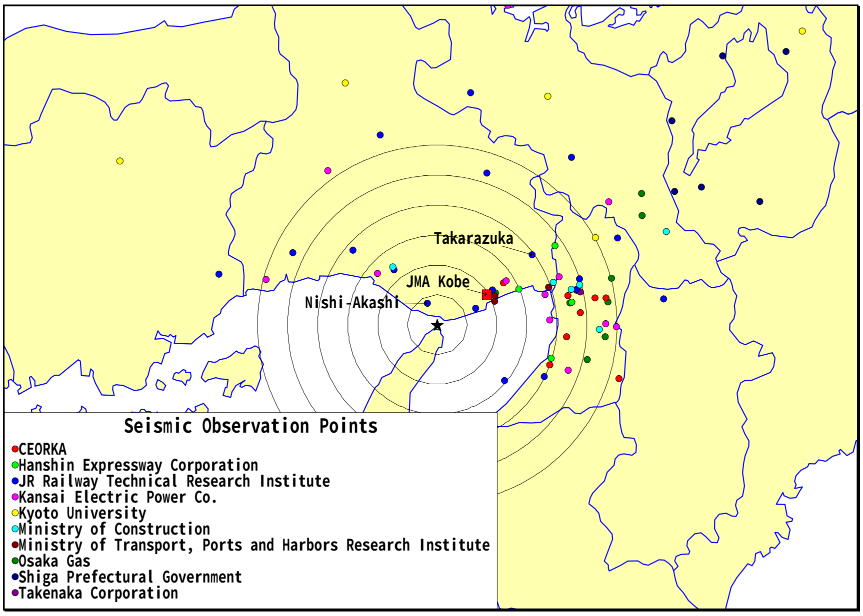


Fig. 2. Locations of seismic observation points and epicenter in the 1995 Kobe earthquake. The distance between each adjacent circle is 10 km.

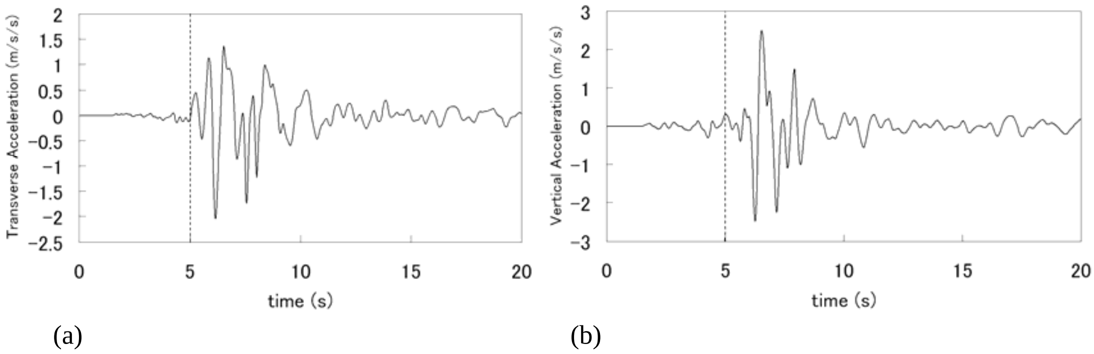


Fig. 3. Response acceleration time histories to (a) the transverse direction and (b) vertical direction of the moving vehicle under the JR Takarazuka record when the vehicle is moving at the speed of 120 km/h.

Based on the assumptions mentioned above, the P-wave is detected 1.4 s after the occurrence of the earthquake at JR Nishi-Akashi station. It takes 4 seconds to issue the EEW after the P-wave detection. At JR Takarazuka station, the S-wave will arrive 11.3 s after the earthquake occurrence. Therefore, the allowance time after receiving the EEW is roughly estimated as 5.9 s. Hence, in the experiment, the EEW is given to the drivers 5 s ahead of the arrival of S-wave, considering the process time for broadcast. The warning message was transmitted by human voice thorough the radio set. The message tells the drivers that an earthquake motion is coming thus reduce speed and stop the vehicle on the road shoulder. It takes 3 s to speak the whole message in Japanese.

As is already mentioned, the vehicle is assumed to be moving near JR Takarazuka station in the experiment. The 3-component acceleration record at JR Takarazuka station was used as the ground motion. The three translational and three rotational motions of a moving vehicle induced by ground motion were calculated using a numerical model of the vehicle [Maruyama and Yamazaki, 2002]. Figure 3 shows the

Fig. 4. Example of the driving simulator experiment to avoid the obstacle during an earthquake without early warning of seismic motion. The examinee crashed to the obstacle.

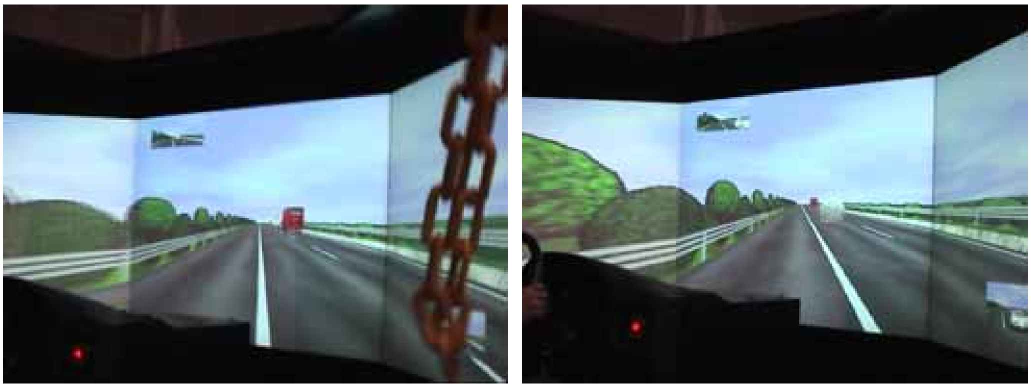


Fig. 5. Example of the driving simulator experiment to avoid the obstacle during an earthquake with early warning of seismic motion. The examinee stopped in the road shoulder.

response acceleration of a vehicle (transverse and vertical components), which was used in the driving simulator experiment.

Twenty-two (22) examinees participated in the driving simulator experiment. Three examinees were in the 30s, three were in the 40s, and the others were in the 20s. The examinees were instructed to drive at the speed of 120 km/h and in the left lane. The examinees were noticed that some announcement may be given during driving, however, they were unknowing that an earthquake motion is applied.

2.2 Results of the experiment

The driving simulator experiment aims to reveal the effects of early warning of seismic motion in avoiding an obstacle appearing ahead of the vehicle. If a large earthquake occurs during driving on an expressway, 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. According to the questionnaire surveys after the actual earthquake in Japan [Kawashima et al., 1989; Maruyama and Yamazaki, 2006], some drivers might not recognize the earthquake occurrence immediately even though they were subjected to a certain level of seismic motion. Therefore, it is anticipated that multiple smashups of moving vehicles will be caused because of these kinds of obstacles. If the drivers can know that a large earthquake is coming, they may escape from the traffic accidents properly.

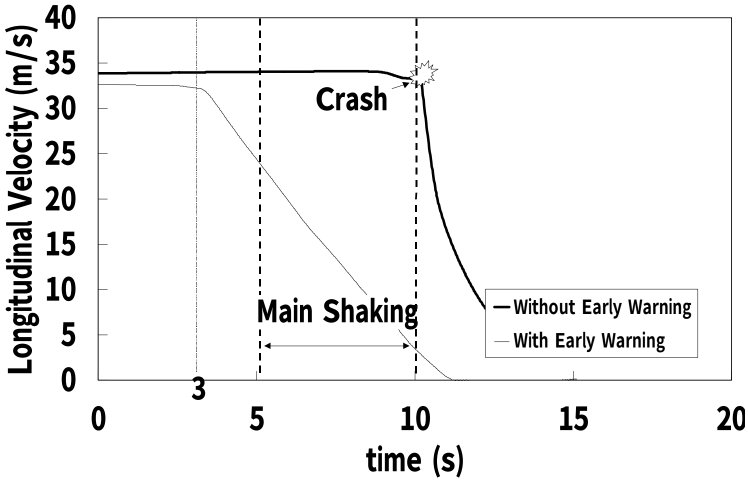


Fig. 6. Comparison of the moving speeds of the examinees with/without early warning of seismic motion.

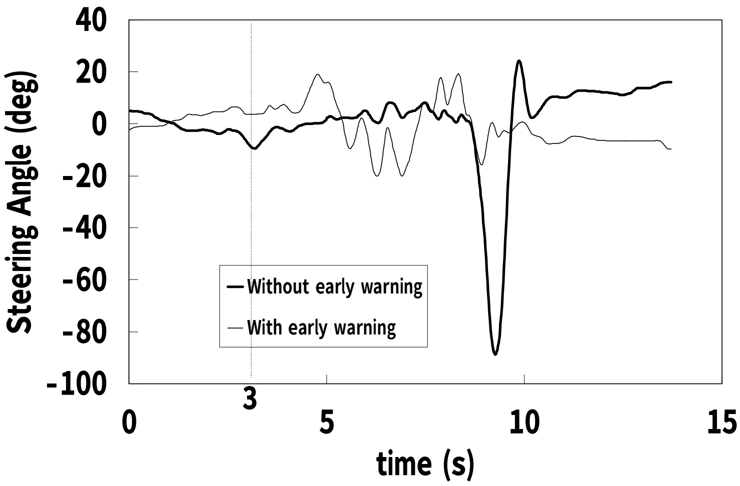


Fig. 7. Comparison of the steering angles of the examinees with/without early warning of seismic motion.

In the experiment, a big stone was inserted in the scenario expressway course as an obstacle in the driving simulator experiment. The stone was set to appear 50 m ahead of the vehicle when the response acceleration of the vehicle showed the largest amplitude. 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. Then, the reactions of the examinees were compared, and the effects of early warning are discussed.

Figure 4 shows the example of the experiment without early warning of seismic motion. The examinee tried to avoid crashing into the obstacle by turning the steering wheel only. Figure 5 shows the example of the experiment when the early warning was given. The examinee did not crash into the obstacle because the message instructed him to stop the vehicle in the road shoulder. Figure 6 compares the moving speeds of these two examinees. The examinee who received the earthquake 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, and then kept on driving at the constant speed. Figure 7 shows the steering angles of the two examinees.

Fig. 8. Two regular driving simulators used in the experiment and the front view from the rear vehicle.

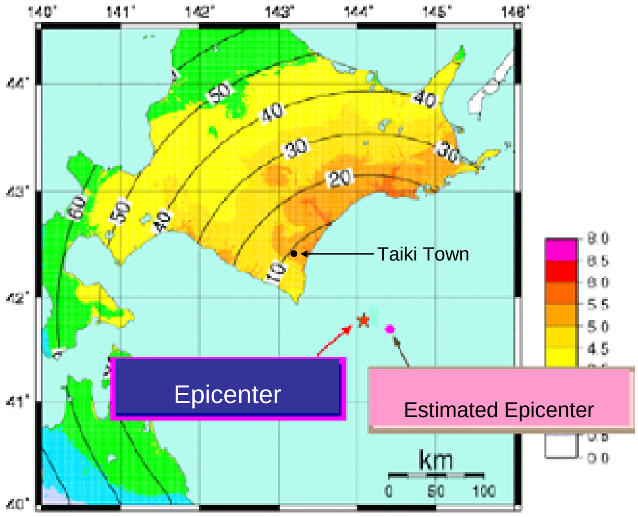


Fig. 9. Allowance time between the EEW and the S-wave arrival in the 2003 Tokachi-oki earthquake simulated by JMA and the location of Taiki Town where the vehicle is assumed to be moving in the experiment.

To escape from the obstacle, the examinee without early warning had only to turn the steering wheel larger than the examinee with early warning.

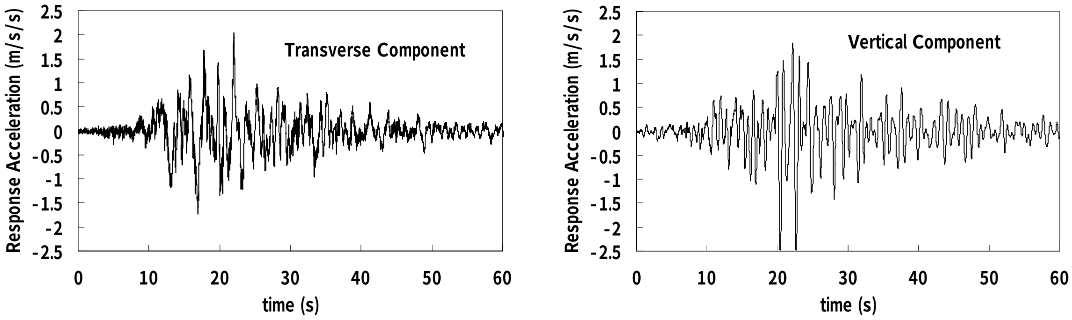
As a whole, the 9 examinees out of 11 without early warning of seismic motion could not avoid traffic accidents. On the other hand, the 9 examinees could avoid crashing into the obstacle when the early warning was given to them. Based on the results, the earthquake early warning is effective to reduce the risk of traffic accidents associated with seismic motion if the vehicle is moving independently.

3. Experiment using Three Synchronized Driving Simulators

3.1. Synchronized driving simulators

Based on the results of the previous chapter, the earthquake early warning (EEW) is somehow effective to drivers on an expressway. However, the interaction among vehicles running together on an expressway under EEW is not considered in the experiment. To realize such situations, plural driving simulators are needed and they should be visualized in the scenario course all together.

Figure 8 shows the driving simulators used in the experiment. Two regular driving simulators and one simple driving simulator that consists of only a steering



(a) (b)

Fig. 10. Response acceleration time histories to (a) the transverse direction and (b) vertical direction of the vehicle under the K-NET Taiki record when the vehicle is moving at the speed of 80 km/h.

wheel, brake and accelerator pedals were employed in the virtual tests, simulating three cars running together on an expressway. The simple driving simulator was driven by a trained person, and it was assigned as a pace maker during the experiment. These driving simulators are developed by Honda Motor Co., Ltd. The regular driving simulators have six servo cylinders to simulate six kinds of motions of a vehicle. These driving simulators are synchronized by main server machine, and they can be observed each other on the expressway course. If a driver turns on the indicator, the light is also visualized on the screen to be watched by the others.

3.2. Outline of the experiment

The condition of an EEW was determined using the locations of the hypocenter and seismometers in the 2003 Tokachi-oki earthquake with JMA magnitude 8.0. Figure 9 shows the allowance time between the EEW and the S-wave arrival simulated by JMA. According to the results of numerical simulation by JMA, the time between receiving the EEW and the arrival of S-wave is about 10 seconds in Taiki Town, which is located about 100 km away from the epicenter. Since an EEW is considered to be effective for this kind of offshore subduction zone earthquakes with large magnitude, we employed this event to investigate the effects of an EEW to expressway drivers.

The 3-component acceleration record at Taiki Town (K-NET Taiki station) was used as an input ground motion in the experiment. Figure 10 shows the response acceleration time histories to the transverse and vertical directions of the vehicle. The instrumental JMA seismic intensity [Shabestari and Yamazaki, 2001] at this site is 5.95 (6 lower), the intensity in which structural damages start to occur and most of the automobile drivers notice the unusual vibration [JMA, 1996].

The computed response acceleration of a vehicle was applied to the actuators of the driving simulator. An earthquake motion was given at the position of the scenario course while vehicles are moving straight as in Fig. 11.

Three types of experiments were conducted in this study. The EEW was given neither the front vehicle nor the rear vehicle in Experiment 1 (14 pairs of drivers). The EEW was transmitted to the both vehicles in Experiment 2 (13 pairs). In Experiment 3, the EEW was given only to the front vehicle, and it was not given to the rear vehicle (14 pairs). The EEW was assumed to be transmitted by car radio, and it announced to the drivers that an earthquake has just occurred and strong motion will arrive soon. It takes about 5 seconds to finish the message. 82 male examinees in total participated in the

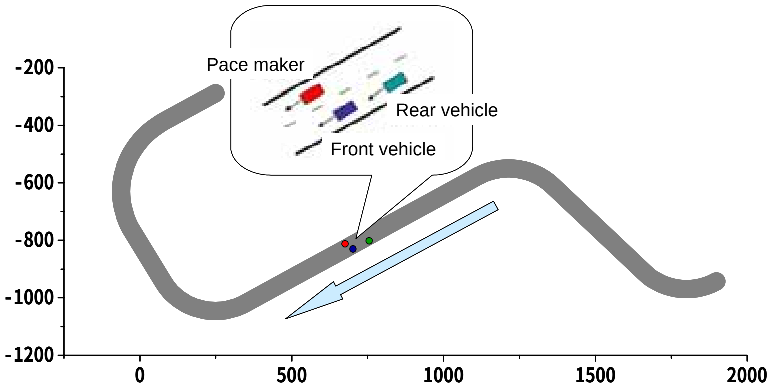


Fig. 11. Scenario highway course in the experiment.

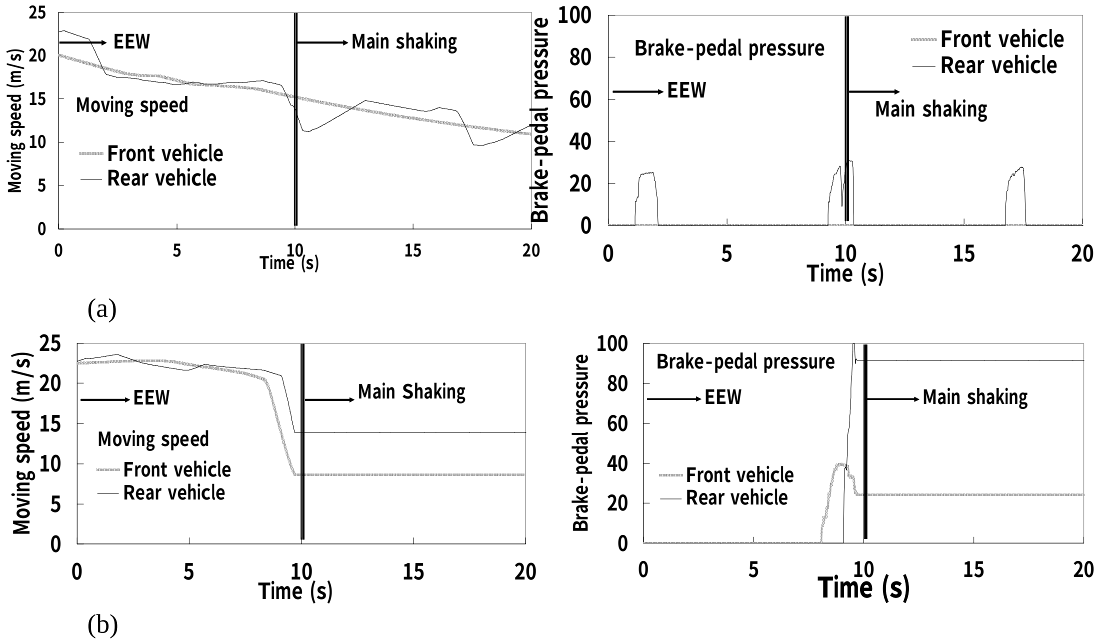


Fig. 12. Example of time histories of moving speed and brake-pedal pressure in (a) Experiments 2 and (b) 3.

experiment and they were instructed to drive at the speed of 80 km/h in the left lane.

3.3. Results of the experiment

In the experiments, the moving speed of vehicle, the positions of brake and accelerator pedals, the angle of steering wheel and so forth were recorded to evaluate drivers' reactions during an earthquake. Figure 12 shows examples of moving speeds of vehicles and brake-pedal pressures observed in Experiments 2 and 3. When the EEW was given to the both examinees (Experiment 2), the front vehicle reduced speed gradually and the rear vehicle put on the brake in phase to keep the distance from the front vehicle. When the EEW was given only to the front vehicle (Experiment 3), the examinee on the front vehicle put on the brake before the S-wave arrival (t = 10 s). Although the examinee on the rear vehicle tried to stop immediately, he eventually crashed to the front vehicle.

After the experiment, questionnaire survey was conducted to each examinee. Figure 13 shows the degree of recognition of the earthquake motion during the

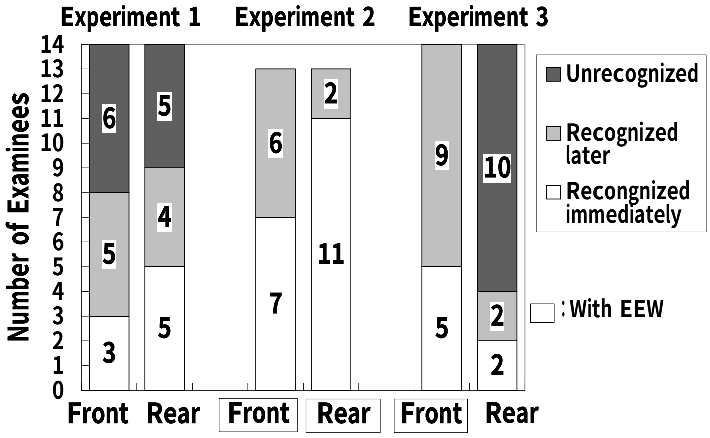


Fig. 13. Degree of recognition of earthquake occurrence during the experiment.

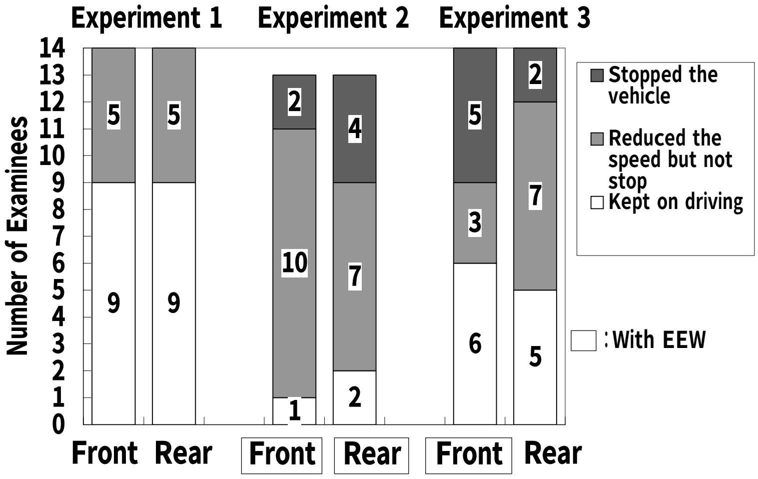


Fig. 14. Reactions of the examinees during strong shaking.

experiments. When the EEW was not transmitted to the drivers, about 40 % of examinees in Experiment 1 and about 70 % of examinees in Experiment 3 (rear vehicle) could not recognize the earthquake occurrence. Figure 14 shows the reactions of the examinees during strong seismic motion. In Experiment 1, more than half of the examinees kept on driving as usual even under strong shaking. On the contrary, many of the examinees in Experiment 2 reduced speed or stopped the car during strong shaking. Owing to the EEW, the examinees in Experiment 2 recognized the earthquake. Hence, they reduced speed or stopped their vehicles to be ready for strong shaking. The results of Experiment 1 indicate that the drivers that are unaware of an earthquake may drive as usual. As for the rear vehicle in Experiment 3, more than half of the examinees reduced speed or stopped the vehicle without recognizing the earthquake because they tried to keep the distance from the front vehicle.

If the EEW is broadcasted by TV and radio, some drivers on the expressway will receive the EEW and the others will not be informed. The similar situations to Experiment 3 easily become a reality. According to Fig. 13, the driver after the one that received the EEW is probably unknowing the earthquake occurrence. As is indicated in Fig. 14, the front vehicle with EEW may reduce the moving speed or stop the vehicle.

The rear vehicle driver without EEW has to react to the front vehicle even though the earthquake is not recognized. Hence, it is afraid that some of them will cause traffic accidents as shown in Fig. 12(b). In this study, two pairs of examinees out of 14 eventually crashed because of the information gap. In addition that, there are some cases that the distance between the two cars became too short and thought to be dangerous.

4. Conclusions and Discussions

In this study, a series of driving simulator experiments were conducted to investigate the effects of earthquake early warning to drivers on the expressway.

According to the results of experiment using single driving simulator, the early warning is possible to contribute to reduce the risk of traffic accidents associated with seismic motion if the vehicle is moving independently. The 9 examinees out of 11 could avoid crashing into the obstacle when the EEW was given to them. Only two examinees could avoid traffic accidents without EEW.

To reveal the effects of EEW on expressway, more realistic situations were considered using three synchronized driving simulators, simulating three cars running together. When an EEW is given only to a part of vehicles running in close distances, the disagreement among drivers' reactions during an earthquake may cause traffic accidents. Such kind of anticipated events were actually occurred in the experiments.

Based on the results, traffic accidents are expected to occur if the EEW is transmitted to the general public. The gap of information, which means some drivers may receive the EEW and the others do not notice the occurrence of an earthquake, will result in the disagreement in driving behavior on the expressway. As one of the countermeasures against the concern, turning on the hazard light after receiving the EEW will be effective. Four examinees on the front vehicle turned on hazard light before reducing the moving speed in Experiment 3. In these cases, the rear vehicles could respond properly even though they did not receive an EEW. The intention to reduce speed of the front vehicle was conveyed to the rear vehicle by turning on hazard light.

Hence, turning on the hazard lights by EEW receivers is considered to be the effective way to make the other drivers ready for an unknown hazard (a coming earthquake) on an expressway. It is important to instruct drivers to turn on the hazard lights before reducing speed when receiving the EEW on an expressway.

References

Allen, R.M. and Kanamori, H. (2003). The potential for earthquake early warning in southern California, *Science*, **300**, pp. 786-789.

Doi, K. (2002). Earthquake early warning system in Japan, *Early Warning Systems for Natural Disaster Reduction*, Springer, pp. 447-452.

Japan Meteorological Agency. (1996). Explanation Table of JMA Seismic Intensity Scale, http://www.jma.go.jp/jma/kishou/know/shindo/explane.html

Japan Meteorological Agency (2007). Earthquake early warning, http://www.jma.go.jp/jma/en/Activities/eew.html

Kawashima, K., Sugita, H., and Kanoh, T. (1989). Effect of earthquake on driving of vehicle based on questionnaire survey, *Structural Eng./Earthquake Eng.*, Japan Society of Civil Engineers, **6**, pp. 405-412.

Lee, W.H.K., and Espinosa-Aranda, J.M. (2002). Earthquake early warning systems: Current status and perspectives, *Early Warning Systems for Natural Disaster Reduction*, Springer, pp. 409-422.

Maruyama, Y., and Yamazaki, F. (2002). Seismic response analysis on the stability of running vehicles, *Earthquake Engineering and Structural Dynamics*, **31**, pp. 1915–1932.

Maruyama, Y., and Yamazaki, F. (2004). Fundamental study on the response characteristics of drivers during an earthquake based on driving simulator experiments, *Earthquake Engineering and Structural Dynamics*, **33**, pp. 775-792.

Maruyama, Y., Yamazaki, F. (2006). Relationship between seismic intensity and drivers' reaction in the 2003 Miyagiken-Oki earthquake, *Structural Eng./Earthquake Eng.*, Japan Society of Civil Engineers, **23**, pp. 69s-74s.

Shabestari, K.T., and Yamazaki, F. (2001). A proposal of instrumental seismic intensity scale compatible with MMI evaluated from three-component acceleration records, *Earthquake Spectra*, **17**, 4, pp. 711-723.

Tong, H., and Yamazaki, F. (1995). Characteristics of strong motion observed in the Great Hanshin Earthquake, *SEISAN-KENKYU*, Institute of Industrial Science, The University of Tokyo, **47**, pp. 270-273 (in Japanese).

Wu, Y.M., Chung, J.K., Chen, C.C., Hsiao, N.C., Shin, T.C., Tsai, Y.B., and Kuo, K.W. (2002). On the establishment of an automatic earthquake information broadcast system in Taiwan, *Early Warning Systems for Natural Disaster Reduction*, Springer, pp. 461-464.