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DRIVING SIMULATOR EXPERIMENT ON THE EFFECT OF EARLY WARNING OF SEISMIC MOTION TO EXPRESSWAY DRIVERS

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SUMMARY

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 moving stability of a vehicle has not been investigated yet. It has been reported that the drivers feel seismically induced vibrations. Because of this phenomenon, they get some difficulties in controlling the vehicles during strong shaking. For a further safety promotion of the expressway networks, it is important to realize the drivers' reactions under seismic motion. In order to investigate the drivers' reactions during an earthquake, the present authors have performed a series of virtual tests using a driving simulator. Based on the results, traffic accidents may occur in case of heavy traffic because of strong shaking. The Japan Meteorological Agency (JMA) has a plan to establish a system to issue "Nowcast Earthquake Information". This information includes the estimated arrival time of the main shaking part of seismic waves, which is 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 may be possible to send an alert to drivers to make them be ready for shaking. In this study, the effect of early warning to drivers is investigated based on the driving simulator experiment. The reactions of drivers with/without warning are compared for different caution time and traffic condition. From the experiment, the early warning is expected to be effective if it is issued to the drivers on the expressways before the arrival of S-wave.

INTRODUCTION

In Japan, some researches on earthquake prediction have been conducted with respect to the coming Tokai Earthquake. However, it is doubtful whether they can predict the coming earthquake properly. When an earthquake occurs, there is a time gap between the arrivals of P-wave and S-wave. Therefore, it has been discussed to send an early warning of seismic motion within this time delay for the purpose of disaster mitigation. In Mexico City, Seismic Alert System (SAS) has already been in an actual use to send the early earthquake warning [1].

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The Japan Meteorological Agency (JMA) is observing seismicity based on the network of seismic stations throughout Japan. They report the JMA seismic intensity, tsunami information, the position of the hypocenter and the JMA magnitude in about two minutes just after the occurrence of an earthquake. As one of the major emphases to mitigate disaster because of an earthquake, they will improve the earthquake information to be applied for the emergency response, for example, providing the spatial distribution of the JMA seismic intensity [2].

They also plan to provide the early earthquake warning, which is called “Nowcast Earthquake Information” [2]. Nowcast Earthquake Information contains the arrival time of S-wave and the magnitude of seismic motion, which are estimated by the P-wave detection near the hypocenter. It is expected that an emergency response and a countermeasure against tsunami disaster are performed rapidly using this information. Railway Technical Research Institute of Japan owns the realtime earthquake disaster mitigation system called UrEDAS (Urgent Earthquake Detection and Alarm System) to stop the Shinkansen Express before the S-wave arrival [3]. In order to extend UrEDAS as a more multipurpose earthquake disaster mitigation system, they are performing trial operations to use Nowcast Earthquake Information [4].

Thus, utilization of time gap between P-wave and S-wave arrivals to send early warning of seismic motion has just begun in Japan. To establish solid and reliable systems to provide Nowcast Earthquake Information is a current issue. However, it will also be important to investigate the effects of early warning in actual situations. The present authors have investigated the moving stability of an automobile under seismic motion based on driving simulator experiments [5]. According to the results, the drivers have difficulties in controlling their vehicles when the JMA seismic intensity is around 6.0, and they protrude their running lane because of strong shaking. Therefore, traffic accidents are possible to occur under strong ground shaking in case of heavy traffic. 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 in the expressway structures.

In this study, a series of driving simulator experiments are conducted to investigate the effects of early warning of seismic motion to drivers on the expressway. The reactions of drivers and the responses to an obstacle appearing ahead of drivers with/without early warning are compared.

ASSUMED NOWCAST EARTHQUAKE INFORMATION

Nowcast Earthquake Information was assumed based on the seismic records and the locations of accelerometers in the 1995 Hyogo-ken Nanbu (Kobe) earthquake (Fig. 1). 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 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 [6].

Nowcast Earthquake Information consists of the 0-th Nowcast Information, which contains the information of earthquake occurrence and the estimated maximum JMA seismic intensity using the first P-wave detection at only one site, the 1st Nowcast Information, which includes the estimated location of the hypocenter and the JMA magnitude using seismic records from 5-6 stations, the 2nd Nowcast Information and the 3rd Nowcast Information, which are refined information using the records from more seismic observation stations [2]. When Nowcast Earthquake Information is applied to the expressway network to make the drivers be ready for strong shaking, the 0-th Nowcast Information is suitable because drivers need some amount of allowance time to reduce the vehicle speed safely.

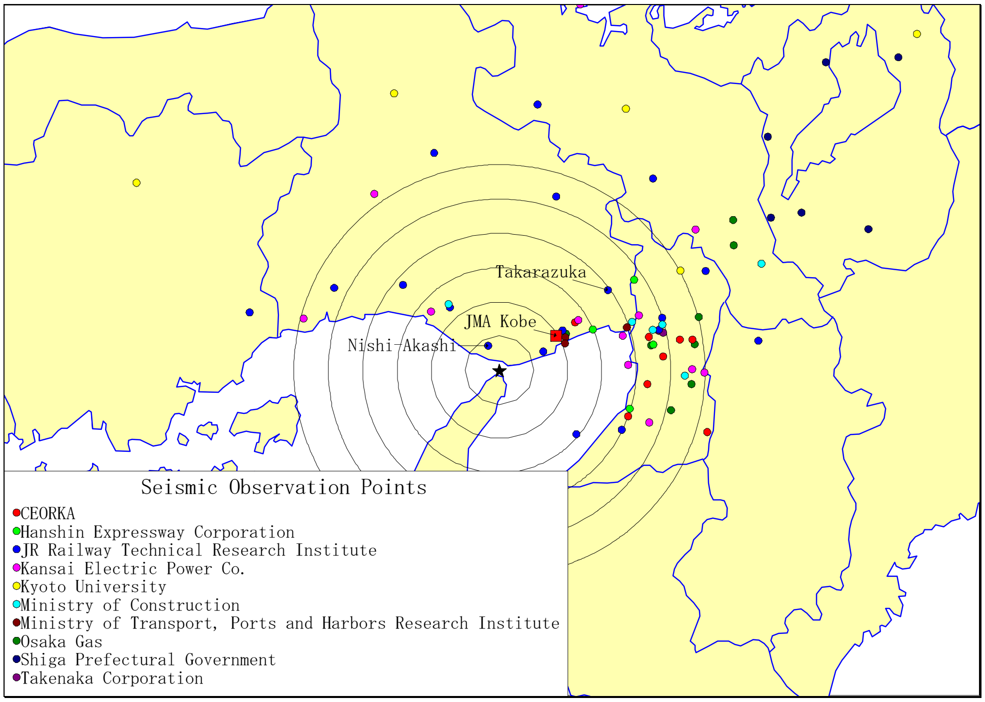
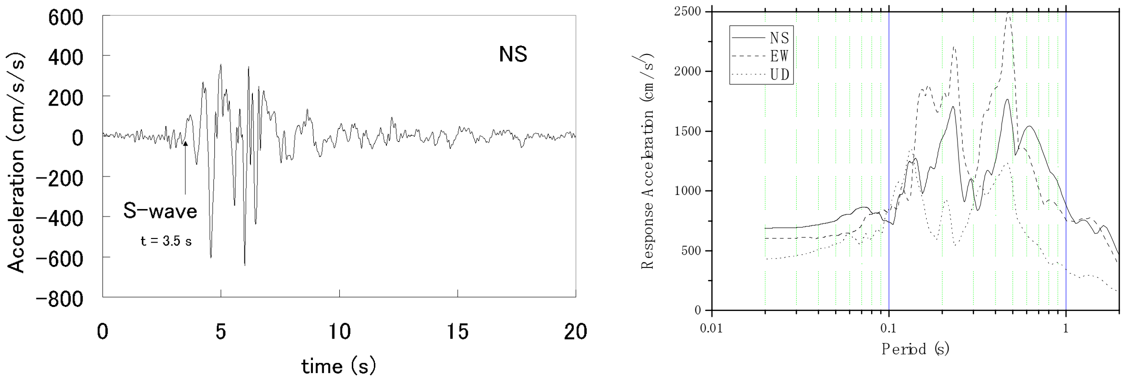


Figure 1. Locations of seismic observation points and epicenter in the 1995 Kobe earthquake. (The distance between each adjacent circle is 10 km.)

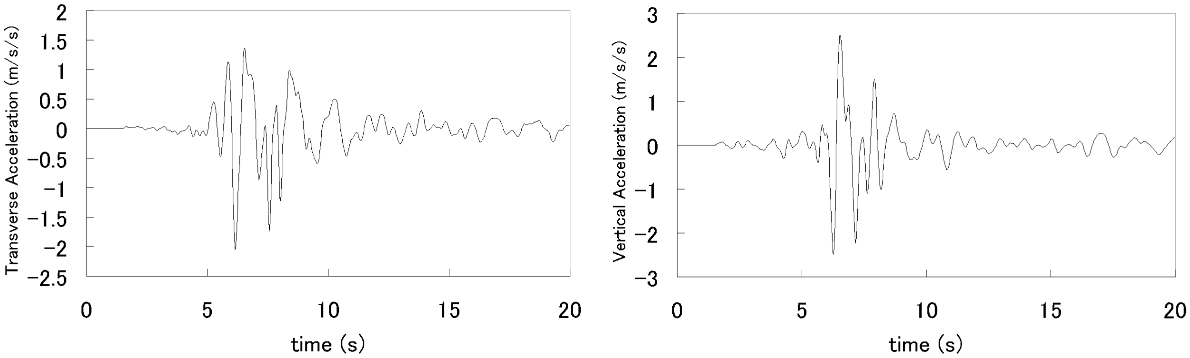


(a) Acceleration time history (b) Response spectra (5% damping)

Figure 2. Acceleration time history and response spectra at JR Takarazuka station in the 1995 Kobe earthquake.

At JR Nishi-Akashi station, the P-wave was 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 was assumed that the earthquake early warning is given to the drivers 5 s ahead of the arrival of S-wave. Figure 2 shows the acceleration time history recorded at JR Takarazuka station in the Kobe earthquake (North-South component) and the acceleration response

Figure 3. Driving simulator used in this study.



(a) Transverse direction

(b) Vertical direction

Figure 4. Response acceleration time histories of the moving vehicle under the JR Takarazuka record scaled to PGA = 6 m/s^2. (Vehicle Speed: 120 km/h)

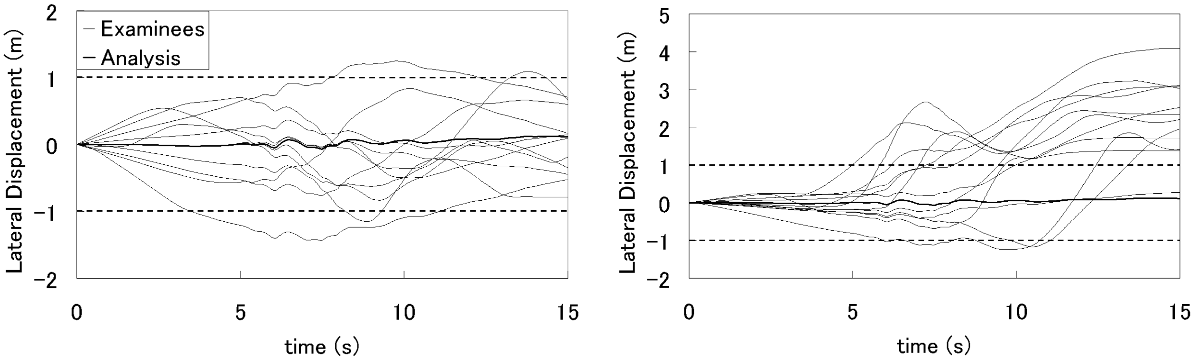
spectra. The arrival of the S-wave was estimated at 3.5 s by the amplitude of acceleration shown in Fig. 2(a).

EFFECTS OF EARLY WARNING OF SEISMIC MOTION

Procedure of driving simulator experiments

Figure 3 shows the driving simulator used in this study [7]. 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. 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.

The possible ways to broadcast the early warning of seismic motion may be electric bulletin board, radio signal, buzzer of mobile phone, car navigation system, and so on. In this study, the warning message was transmitted by human voice assuming the radio set is turned on automatically. The message tells the drivers that an earthquake motion is coming thus reduce speed and stop the vehicle in the road shoulder. It takes three seconds to speak the whole message in Japanese.



(a) Without early warning of seismic motion (b) With early warning of seismic motion

Figure 5. Comparison of running trajectories of the vehicle with/without early warning of seismic motion under the JR Takarazuka record scaled to PGA = 6 m/s^2.

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 was used as the ground motion in the experiment. The North-South component was applied to the transverse direction of the moving vehicle, and its peak ground acceleration was scald to be 6 m/s^2. The absolute response accelerations of the moving vehicle [8] are shown in Fig. 4. It should be noted that the ground acceleration was filtered in the frequency range of 0.2-5.0 Hz considering the reproducibility of motion by the driving simulator [5].

Experiment 1: Comparison of drivers' responses with/without early earthquake warning

Twelve (12) examinees participated in this driving simulator experiment. All examinees are the students of The University of Tokyo. Therefore, their driving careers were recognized to be similar among them. Each of them was requested to drive twice. The early warning of seismic motion was not given in the first driving. However, it was given 5 s ahead of the S-wave arrival in the second driving. Then, their reactions to seismic motion with/without early warning were compared. Before conducting the second experiment, the examinees were informed that a message would be announced during driving, but the content of the message was not explained.

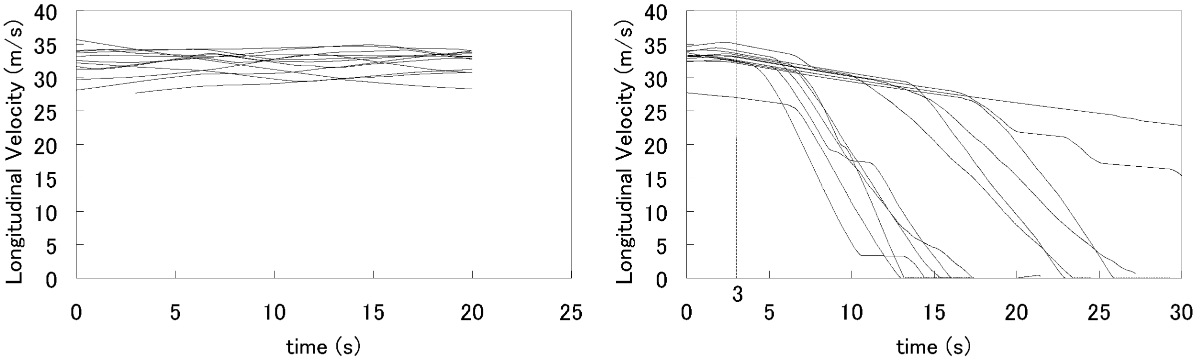
The running trajectories for all examinees were calculated as

$$v = v_{seism} + v_{driver} \tag{1}$$

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

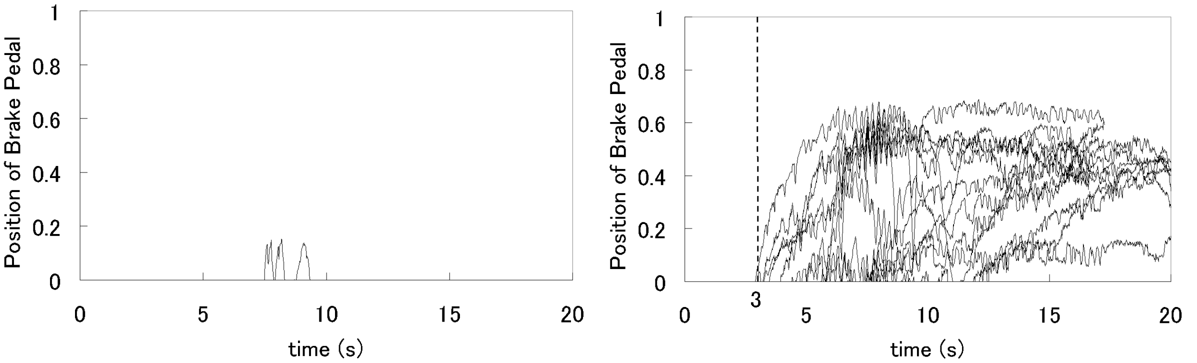
$$\dot{Y} = u \sin\psi + v \cos\psi \tag{3}$$

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 [8]. 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 (3). Figure 5 shows the running trajectories of all examinees with/without early warning. The result from the seismic response analysis of the moving vehicle without considering the driver's reaction [8] is also shown in Fig. 5. The results show that four examinees protruded their running lane because of strong shaking without early warning of seismic motion. Here, considering both the width of the vehicle and that of a single lane of an expressway (3.6 m), the course deviation of 1 m means that the driver shifted to the adjacent lane. It is also seen that many of them were winding their way under earthquake motion without early warning. On the other hand, when the early warning of seismic motion was given to the examinees, many of them were



(a) Without early warning of seismic motion (b) With early warning of seismic motion

Figure 6. Longitudinal velocities of the examinees with/without early warning of seismic motion.



(a) Without early warning of seismic motion (b) With early warning of seismic motion

Figure 7. Position of the brake pedal of the examinees with/without early warning of seismic motion.

not windling during strong shaking. It should be noted that these two tests for each examinee were conducted at the interval of more than 10 minutes to avoid getting accustomed to driving during shaking.

Figure 6 shows the longitudinal velocities for the examinees with/without early warning. The longitudinal velocities are almost constant because the examinees did not put on a brake during strong shaking without early warning (Fig. 7(a)). However, when the early warning was given, the examinees reduced the vehicle speed because they were instructed to stop the vehicle in the road shoulder. The examinees who showed the rapid responses to the early warning began to put on the brake at 3 s, when the message was just finished (Fig. 7(b)). The position of the brake pedal is 1.0 (Fig. 7) when the examinee made the full brake. This may be one of the reasons that the examinees were not winding their way during strong shaking if the early warning of seismic motion was given.

Figure 8 shows the relationship between the time and the traveling distance when the examinees started to cross the road shoulder and stopped completely in the second experiment. Both the time and the distance are counted from the beginning of the message of early warning. The result of each examinee is shown by each line segment. The origination of the line indicates the time and the traveling distance when the examinee started to cross the road shoulder. According to the figure, many of the examinees began to shift to the road shoulder at 5-10 s, when they were subjected to the main part of strong motion. It took about

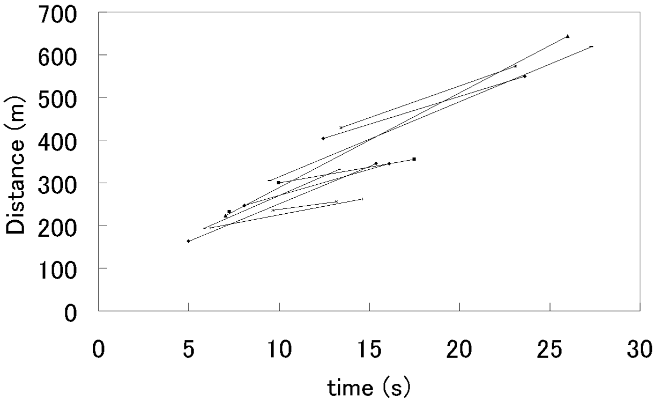


Figure 8. Relationship between the time and the traveling distance when the examinees started to cross the road shoulder and stopped completely with early warning of seismic motion.

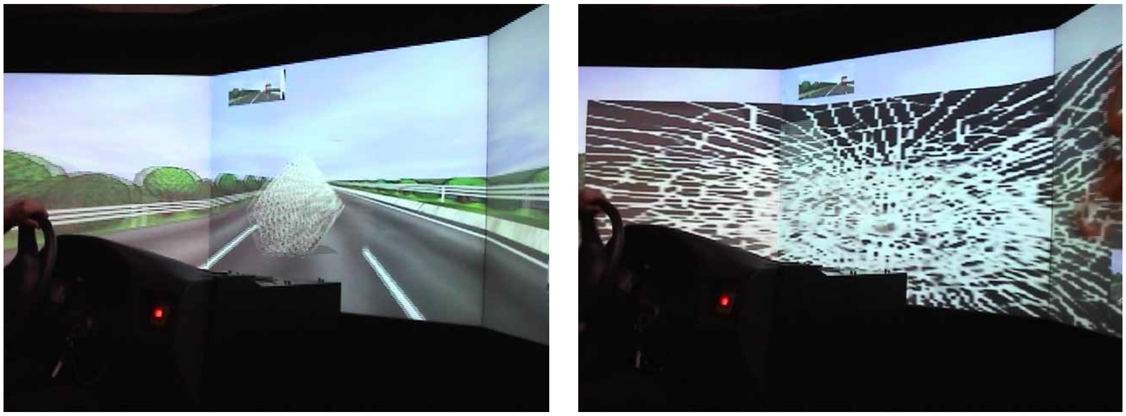


Figure 9. Example of the driving simulator experiment to avoid the obstacle during an earthquake without early warning of seismic motion.

15 s or 25 s to stop the vehicle completely after receiving the early warning. They traveled about 300 m or 600 m until their vehicles stopped completely.

Experiment 2: Effect of early warning of seismic motion to avoid the obstacle

This 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. It is not denied 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.

In Experiment 2, twenty-two (22) examinees participated. Three examinees were in the 30s, three were in the 40s, and the others were in the 20s. 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.

A big stone was inserted in the scenario highway course as an obstacle in the driving simulator experiment. The stone was set to appear 50 m ahead of the vehicle at 8 s, when the response acceleration

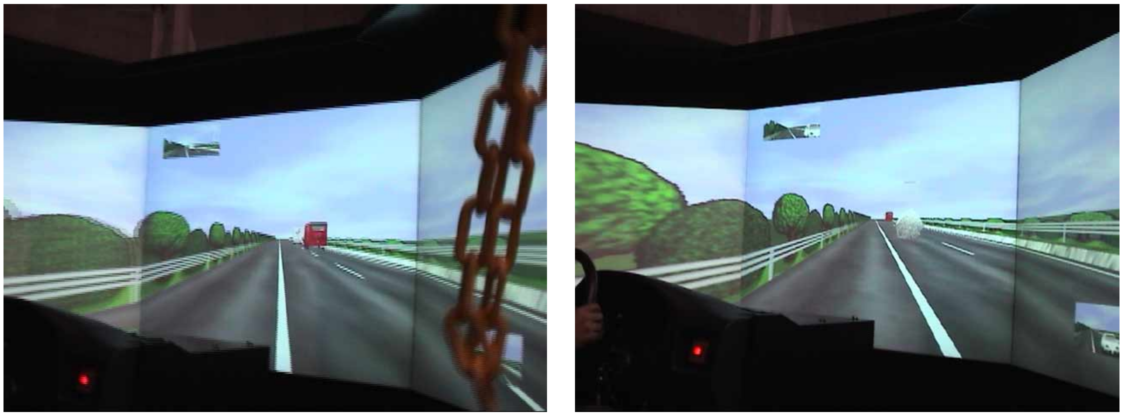
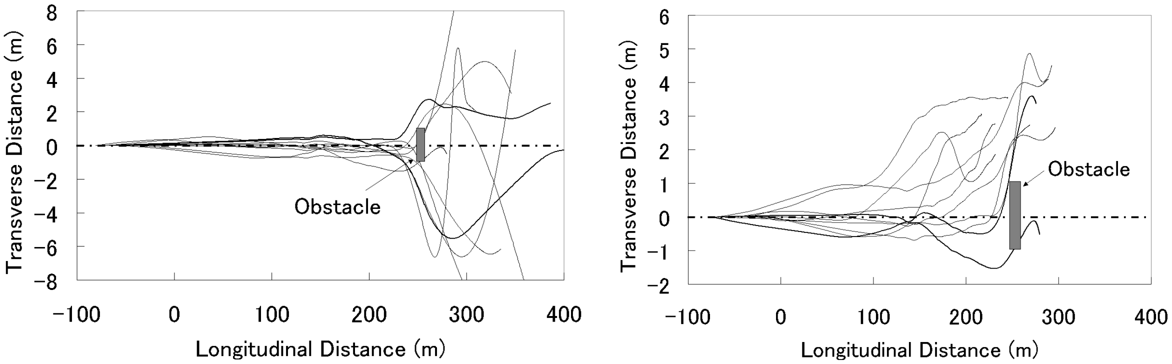
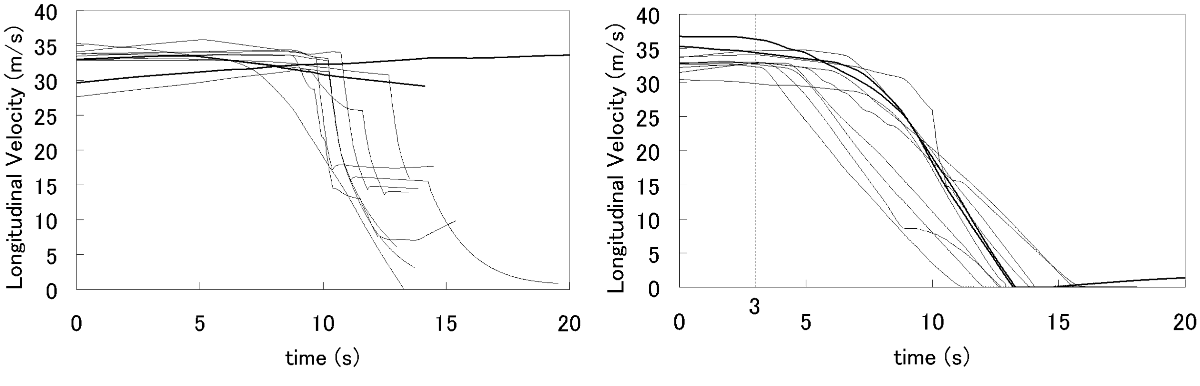


Figure 10. Example of the driving simulator experiment to avoid the obstacle during an earthquake with early warning of seismic motion.



(a) Without early warning of seismic motion (b) With early warning of seismic motion

Figure 11. Running trajectories to avoid the obstacle appearing ahead of the vehicle during an earthquake.



(a) Without early warning of seismic motion (b) With early warning of seismic motion

Figure 12. Longitudinal velocities of the examinees to avoid the obstacle appearing ahead of the vehicle during an earthquake.

of the vehicle showed the largest amplitude (Fig. 4). Figure 9 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 10 shows the example of the experiment when the early warning was given. The examinee did not crash into the obstacle because the message instructed to stop the vehicle in the road shoulder.

Figure 11 shows the running trajectories of the examinees. In the figure, the position of the obstacle was shown as 250 m in the *X*-axis for all the examinees. Thin lines in Fig. 11(a) show the running trajectories of the examinees who failed to avoid the obstacle, and bold lines show those of the examinees who could escape from the obstacle successfully. The 9 examinees out of 11 could not avoid traffic accidents because of the obstacle shown ahead 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 (thin lines in Fig. 11(b)). The running trajectories of the two examinees who failed escaping from the obstacle are shown in bold lines in Fig. 11(b).

Figure 12 shows the longitudinal velocities of the examinees with/without early warning of seismic motion. The bold lines in Fig. 12(a) show the longitudinal velocities of the examinees who could avoid the obstacle without early warning and those in Fig. 12 (b) show the velocities of the examinees who could not avoid it with early warning. The examinees drove the vehicle without putting on the brake when the early warning was not given. Therefore, the longitudinal velocity is almost constant during strong shaking. Note that the vehicle speed changed suddenly at around 10 s because the vehicles crashed into the obstacle.

It can be said that the examinees tried to avoid crashing only by means of turning the steering wheel when the early warning was not given. On the contrary, the examinees who were given early warnings could avoid the traffic accidents because they put on the brake due to the message and the vehicle speed became smaller owing to putting on the brake. Thus, the examinees could escape the obstacle easily by means of braking and turning the steering wheel. Hence, it is concluded that early warning of seismic motion can reduce traffic accidents if it is issued properly and promptly.

CONCLUSION

In this study, the effects of early warning of seismic motion to the drivers on expressway were investigated based on the driving simulator experiments. The early warning of seismic motion was given to the examinees 5 s ahead of the S-wave arrival considering the locations of the epicenter and seismic observation stations in the 1995 Kobe earthquake. Due to the early warning, the examinees could reduce the vehicle speed just before the main part of seismic motion and they did not wind their way during strong shaking.

The reactions of the examinees with/without early warning were compared in escaping from the obstacle which appeared ahead of the vehicle. When the early warning was given, the 9 examinees out of 11 could avoid crashing into the obstacle. On the contrary, the 9 examinees out of 11 caused the traffic accidents without early warning of seismic motion. The reason why the examinees with early warning of seismic motion could escape from the obstacle is they could reduce the vehicle speed just before the arrival of S-wave due to the warning message.

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. 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.

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