Experiments of Earthquake Early Warning to Expressway Drivers Using Synchronized Driving Simulators

Yoshihisa Maruyama,[a)] Fumio Yamazaki,[a)] M.EERI, and Masato Sakaya[b)]

To reduce the casualties and impacts resulting from earthquakes, the Japan Meteorological Agency (JMA) introduced its earthquake early warning (EEW) system to the general public on 1 October 2007. Interestingly, a side effect of the system is an anticipated increase in traffic accidents that may occur because the EEW transmission will not be received by all drivers. Consequently, the effects of an EEW are investigated using three synchronized driving simulators to replicate the conditions of three cars traveling in close proximity on an expressway. When the EEW was received by all cars, the drivers behaved properly, and no problems occurred. When an EEW was received by just one car, however, some drivers reduced speed immediately, and accidents resulted in two out of 14 test cases. These experiments show the necessity of educating the public on how to respond if an EEW is received while driving on an expressway. In such situations, activating hazard lights and reducing speed gradually is suggested to avoid traffic accidents. [DOI: 10.1193/1.3104862]

INTRODUCTION

After the 1985 Mexico earthquake, a seismic alert system was designed and implemented in Mexico City. This system, named the Seismic Alert System (SAS), consists of four components: seismic detection, telecommunications, central control, and radio warning (Lee and Espinosa-Aranda 2002). When the 14 September 1995 Copala Earthquake occurred in the Mexican state of Guerrero, the SAS early warning was activated, and the majority of the nation's AM/FM radio stations broadcasted an alert signal to the public. A similar system, the Taiwan Rapid Earthquake Information Release System (TREIRS), has been operated in Taiwan since March 3, 1996 (Wu et al. 2002). Allen and Kanamori (2003) discussed the potential benefits of earthquake early warning in southern California and showed that an earthquake alarm system could issue a warning anywhere from a few seconds to tens of seconds ahead of damaging ground motion. In some earthquake-prone regions, EEW systems are expected to play an important role in risk management efforts (Iervolino et al. 2006; Erdik et al. 2003).

After the 1995 Kobe earthquake, the Japan Meteorological Agency (JMA) began efforts aimed at providing earthquake early warning (EEW) information that would contain the expected arrival time of S-wave and anticipated intensity of seismic motion es-

[a)] Graduate School of Engineering, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan
[b)] Former Student, Faculty of Engineering, Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

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timated from the P-wave detected near the hypocenter (Doi 2002). Due to the advances in seismic observation networks and the developments of communication technology, Japan's EEW was mostly finalized by 2005. It was expected that the emergency preparations for strong shaking and tsunami occurrence could start based on an EEW, and that such a system would allow emergency responses to be performed more rapidly and efficiently. Furthermore, the Railway Technical Research Institute of Japan (RTRI) owns and operates a real-time earthquake disaster mitigation system called UrEDAS (Urgent Earthquake Detection and Alarm System), which is designed to stop the Shinkansen Express trains (bullet trains) before the arrival of the S-wave of an earthquake (Nakamura 1988). In order to expand UrEDAS into a multipurpose earthquake disaster mitigation system, the RTRI and JMA decided to cooperate with each other and integrate their EEW systems.

Japan's EEW has been in operation on a trial basis since August 2006. Since that time, EEW information has been transmitted to construction sites, railways, factories, and other locations where the EEW information has been utilized properly without problems or confusion. Based on the results of those trial operations, the JMA announced it would begin broadcasting EEW information to the general public via radio and TV signals starting 1 October 2007 (JMA 2007). While overall effects are expected to be positive, it is anticipated that some problems may occur when an EEW is issued to the general public because panic could ensue and crowd stampedes could form at the exits of theaters and department stores.

In hopes of minimizing such occurrences, the JMA compiled a lists of "dos and don'ts" for the general public, explaining what they should and should not do upon receiving an EEW (JMA 2007). This guidance covered a number of situations, including proper behavior while driving an automobile. Despite this, EEW-related traffic accidents remain anticipated because the transmitted EEW signals are not expected to be received by all expressway drivers. Maruyama and Yamazaki (2004) demonstrated the possible effects of EEW reception on expressway drivers using a driving simulator. In that study, it was found that receipt of an EEW allowed most test subjects to avoid those obstacles simulating the structural damage caused by the earthquake. Hence, it is believed that the EEW system can prevent some traffic accidents, such as the one that killed a police officer after the Newhall Pass interchange collapsed during the 1994 Northridge earthquake (EERI 1995). According to questionnaire surveys (Kawashima et al. 1989, Maruyama and Yamazaki 2006), drivers may not notice an earthquake in progress, even though they are being subjected to strong seismic motion. However, drivers who receive an EEW can use the advanced warning of the impending quake to reduce speeds or stop, and are thus less likely to collide with collapsed bridge sections or encounter other quake-related damage.

However, no other vehicles were considered except for those driven by the test subjects in our previous study (Maruyama and Yamazaki 2004), and it has since become important to consider and observe the interaction among vehicles operating in close proximity on an expressway when an EEW is issued. In this study, such situations are

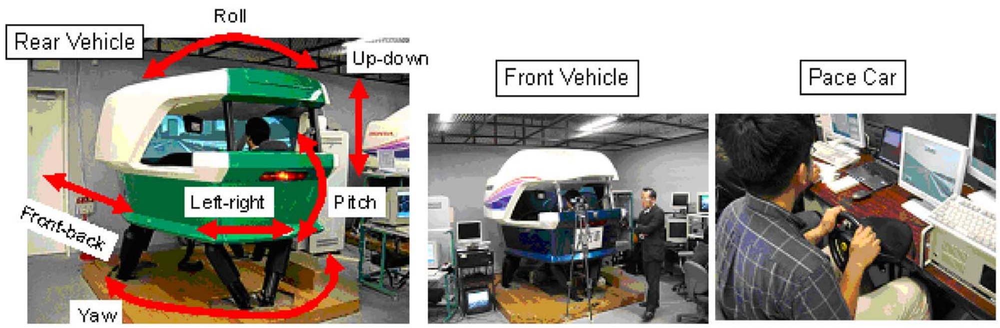

Figure 1. Two full scale and one simple driving simulators used in this study. These driving simulators are connected by a server to be synchronized.

realized using three synchronized driving simulators connected by a server. The reactions of the drivers are observed under various EEW reception conditions, and the overall effects of the EEW on expressway drivers are investigated.

OUTLINE OF THE DRIVING SIMULATOR EXPERIMENTS

Figure 1 shows the driving simulators used in this study (Honda Motor Co., Ltd. 2001). Two full-scale driving simulators and one simple driving simulator (consisting of a steering wheel, brake, and accelerator pedals only) were employed in virtual tests to simulate three cars operating in close proximity on an expressway. The full-scale driving simulators have six axis servo cylinders and can mimic six separate vehicle motion (three translational and three rotational) components. All driving simulators are connected by a main server, and each are displayed visually to the others via their respective view screens. The turn indicators, brake lights, and hazard lights are also displayed on the view screens of the respective driving simulators. Figure 2 shows the scenario expressway course used in the experiment. The test subjects were instructed to drive at a speed of 80 km/h in the left lane (regular speed lane in Japan). In the right (fast speed) lane, the simple driving simulator, operated by a trained simulator operator, was assigned as a pace-car during the experiment.

The EEW condition was set by assuming the hypocenter and the locations of seismometers in the 26 September 2003 Tokachi-oki earthquake, which occurred with a JMA magnitude of 8.0. Based on the results of numerical simulations performed by JMA, the time between receiving the EEW and the arrival of the S-wave was determined to be about 10 seconds at Taiki Town (the simulated location of the test), which is about 100 km away from the epicenter. Since an EEW is considered to be effective for this kind of large offshore subduction zone earthquake, we utilized this event to investigate the effects of an EEW on expressway drivers.

EEWs issued by JMA provide advanced announcement of the estimated seismic intensities and expected arrival time of principal motion through TV and radio broadcasts. On TV, screen-generated characters and graphic warnings show the areas where the JMA

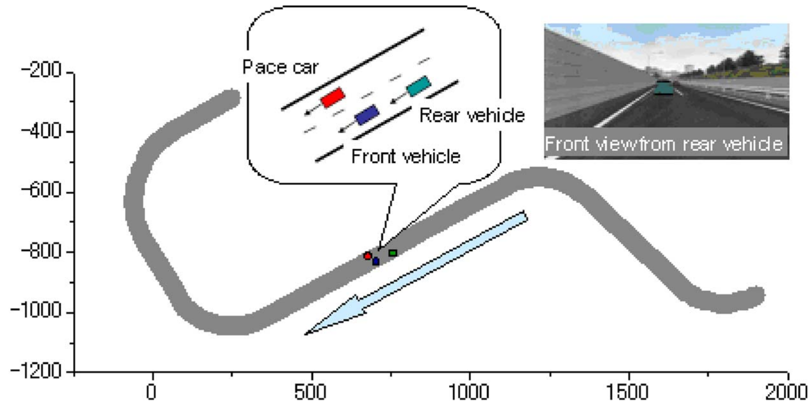

Figure 2. Scenario expressway course in the experiment. The three vehicles can see one another through windows and mirrors.

expects seismic intensity to be equal to or larger than 5.0 (5 upper) and is then followed by an electronic alert sound. For radio, warnings for the anticipated areas are broadcast by electronic voice announcement. With these procedures in mind, the EEW provided in the experiments simulate the information that could be expected to be transmitted via car radio, warns the drivers that an earthquake has just occurred, and that strong motion will arrive soon. It takes about 5 seconds to convey the message.

The three-component acceleration record (Figure 3) at K-NET (Kinoshita 1996) Taiki station was used to simulate seismic motion in the experiments. The acceleration response spectra were also calculated and shown in the figure. The instrumental JMA seismic intensity (Shabestari and Yamazaki 2001) recorded at this site was 5.95 (6 lower), the intensity at which structural damages start to occur and when most automobile drivers notice unusual vibration (JMA 1996).

The seismic response acceleration of a moving vehicle was calculated (Maruyama and Yamazaki 2002). A model vehicle with a six-degree-of-freedom system was employed (Figure 4) and the equations demonstrating the motion of the vehicle in the longitudinal and transverse directions (including the effect of seismic motion) are defined as

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

$$m(\dot{v} + ur - \ddot{x}\sin\psi + \ddot{y}\cos\psi) = \sum_i \sum_j (F_{xij}\sin\delta_{tij} + F_{yij}\cos\delta_{tij}) \tag{2}$$

where

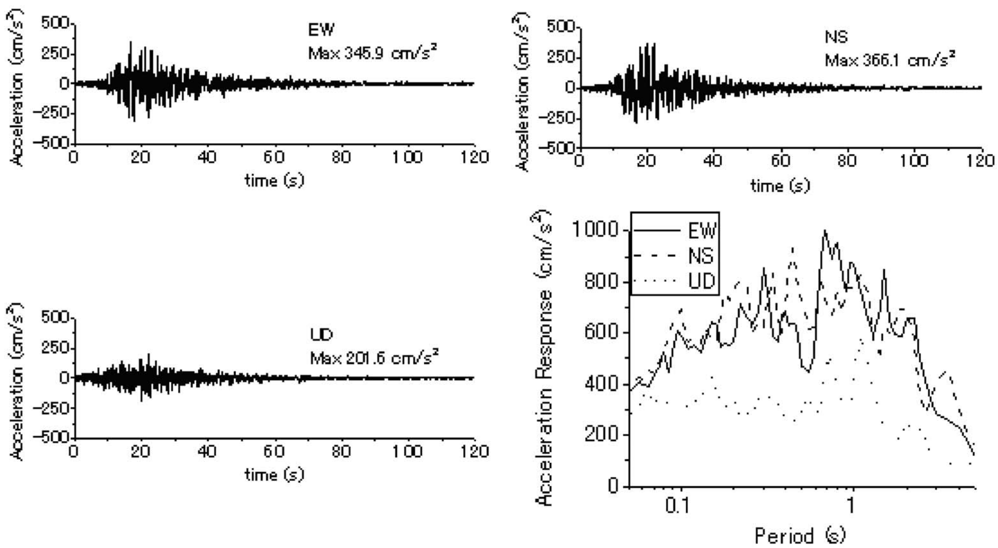

Figure 3. Acceleration time histories recorded at K-NET Taiki during the 2003 Tokachi-oki earthquake and their acceleration response spectra with 5% damping ratio.

- $\ddot{x}$ and $\ddot{y}$ are the ground accelerations in 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
- 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.

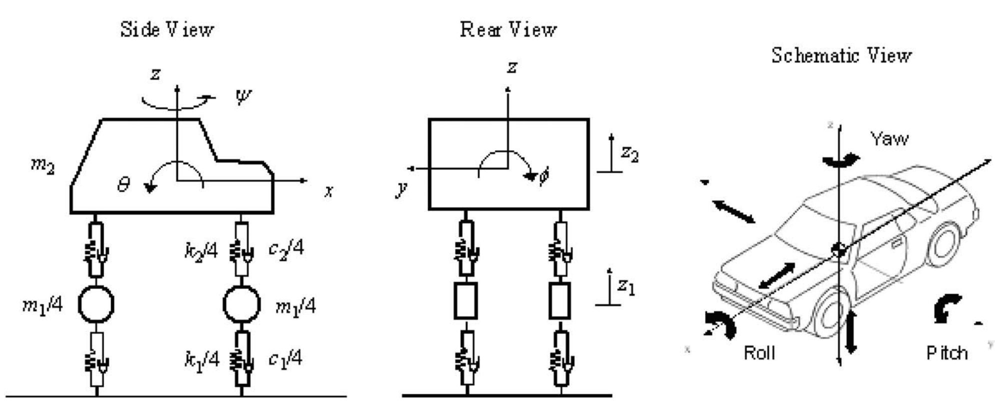

Figure 4. Vehicle model with six-degrees-of-freedom used in this study.

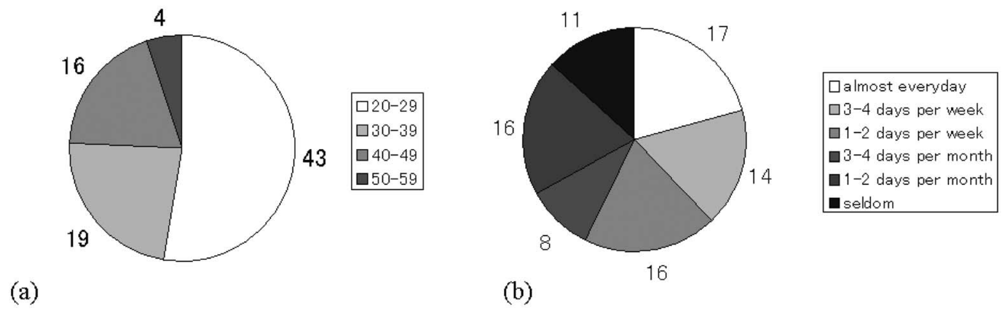

Figure 5. Distributions of (a) the age and (b) driving frequency of the examinees.

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. The equations of motion of the vehicle to the vertical direction are described as:

$$m_1(\ddot{\zeta}_1+\ddot{z}_{in})+c_1\dot{\zeta}_1+c_2(\dot{\zeta}_1-\dot{\zeta}_2)+k_1\zeta_1+k_2(\zeta_1-\zeta_2)=0 \tag{3}$$

$$m_2(\ddot{\zeta}_2+\ddot{z}_{in})+c_2(\dot{\zeta}_2-\dot{\zeta}_1)+k_2(\zeta_2-\zeta_1)=0 \tag{4}$$

where z_{in} is the vertical displacement of the ground. $\zeta_1(=z_1-z_{in})$ and $\zeta_2(=z_2-z_{in})$ are the relative vertical displacements of m_1 and m_2, respectively. Three kinds of rotational motion, (pitching motion, θ, rolling motion, ϕ, and yawing motion, ψ) are also calculated as per our previous research (Maruyama and Yamazaki 2002).

The computed response acceleration of a vehicle was applied to the actuators of the driving simulator. An earthquake motion was provided to the vehicles in the straight segment of the scenario course as shown in Figure 2.

Three types of experiments were conducted in this study. In Experiment 1, no EEW was provided to either the front vehicle or the rear vehicle (14 pairs of drivers). In Experiment 2, an EEW was transmitted to the both vehicles (13 pairs). In Experiment 3, the EEW was provided only to the front vehicle and was not provided to the rear vehicle (14 pairs). A total of 82 male test subjects, with a broad range of ages and driving experience (Figure 5), participated in the experiment. The test subjects were informed that some announcements may be sent during the driving simulation but were not informed that earthquake motion would be applied.

RESULTS OF QUESTIONNAIRE SURVEY AFTER THE EXPERIMENTS

After the experiment, each test subject was requested to complete a questionnaire. Figure 6 shows the degree of recognition of earthquake motion during the experiments. When the EEW was not transmitted to the drivers, about 40% of the test subjects in Experiment 1 and about 70% of the test subjects in Experiment 3 (rear vehicle) were

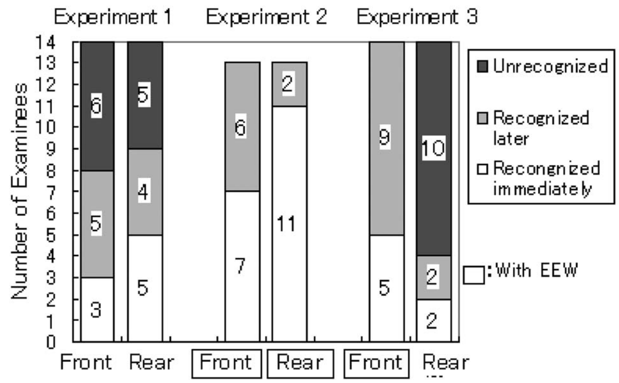

Figure 6. Degree of recognition of earthquake occurrence during the experiment.

unable to recognize the earthquake occurrence. A similar tendency was also pointed out under the actual earthquake environment (Kawashima et al. 1989; Maruyama and Yamazaki 2006).

Alternatively, all test subjects recognized the earthquake occurrence when an EEW was provided. If road embankment failures or road surface cracks are generated due to an earthquake, motorists who are unaware of the earthquake occurrence may drive directly into the damaged segment of a roadway. It is well known that this is precisely what occurred to two automobiles, which fell to the lower surface of the highway, when a segment of the San Francisco-Oakland Bay Bridge collapsed during the 1989 Loma Prieta earthquake (USGS 2005). Thus, it is clear that drivers who receive advanced warning of impending earthquake occurrence by EEW can avoid these kinds of traffic accidents, and it appears that the EEW system can be very effective in this regard.

In Experiment 3, the test subjects of the front vehicle were able to recognize the earthquake occurrence due to reception of an EEW, while the test subjects of the rear vehicle might remain unaware of it. The difference in earthquake recognition between the two sets of drivers can be expected to affect driving behavior during an earthquake. Figure 7 shows the reactions of the test subjects during strong seismic motion. In Experiment 1, more than half of the test subjects kept on driving normally, even though they were subject to strong shaking. Alternatively, many of the test subjects in Experiment 2 reduced speed or stopped their car when strong shaking was in progress. This shows that, due to the EEW, the test subjects in Experiment 2 recognized the earthquake occurrence and reduced speed or stopped their vehicles in anticipation of strong motion. The results of Experiment 1 indicate that drivers who are unaware of an earthquake may continue driving as usual. As for the rear vehicle in Experiment 3, less than half of the test subjects kept driving as usual, even though they did not recognize the earthquake occurrence, because they reacted to maintain a proper distance from the vehicle ahead of them which had reduced speed or stopped.

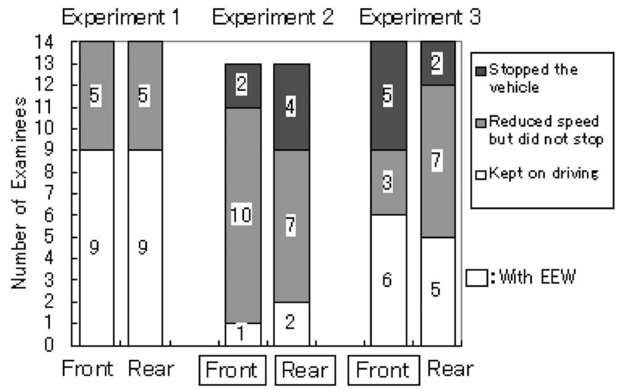

Figure 7. Reactions of the test subjects during strong shaking.

The test subjects driving the front vehicle that reduced speed or stopped were questioned as to whether they had confirmed their distance from the rear vehicle by use of the rearview mirror (Figure 8). Only one test subject confirmed the presence of the rear vehicle by mirror use without having first received an EEW (Experiment 1). In Experiment 1, four out of five test subjects reduced speed without confirming their separation distance from the following vehicle. In Experiments 2 and 3, more than 60% of the total test subjects checked the mirror before reducing speed. The EEW was transmitted ten seconds ahead of the S-wave arrival in these experiments. As a result, most test subjects that received the EEW could afford the time to check their rearview mirror and confirm the distance separating the two vehicles. Based on these results, the arrival of an EEW appears to be effective in adding additional safety leeway prior to the arrival of strong seismic motion.

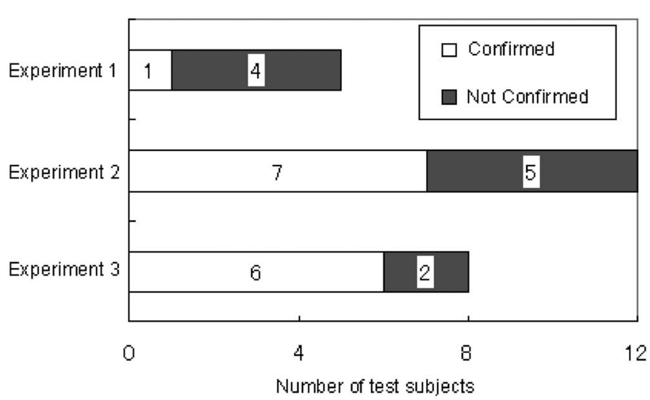

Figure 8. Degree of confirmation of the distance from the rear vehicle by rearview mirror.

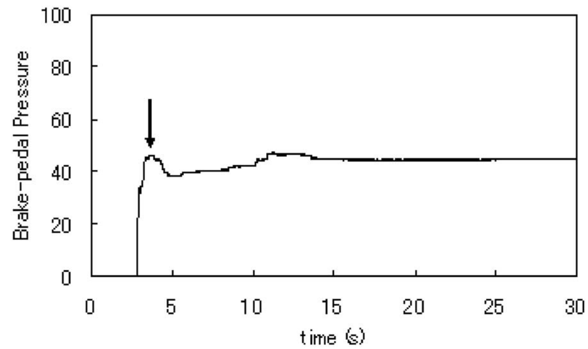

Figure 9. Example of brake-pedal pressure during driving (Experiment 2) and extraction of the maximum brake-pedal pressure and its associated time.

ANALYSIS OF DRIVERS' RESPONSES BASED ON CHRONOLOGICAL EXPERIMENT LOGS

The reactions of the test subjects were recorded using a PC during the experiments. The simulator is capable of recording chronological log information for a total of ten response variables, e.g., vehicle position, operating speed, accelerator pedal position, and so on.

Brake-pedal pressure was investigated from these chronological logs (as shown in Figure 9), and the times associated with the maximum brake-pedal pressure were extracted for each test subject. Figure 10 shows the results for Experiments 1 and 2. Most of the test subjects who applied brakes in Experiment 1 did so after the main shaking part had arrived ($t=10$ s). In Experiment 2, due to the received EEW, almost all of the test subjects applied their brakes prior to the arrival of the strong seismic motion. Figure 11 shows the speeds of the front vehicles in Experiments 1 and 2. The test subjects in Experiment 1 drove at the speed of 80 km/h (22.2 m/s), as instructed, even after main seismic motion had arrived because many of them did not recognize that an earthquake

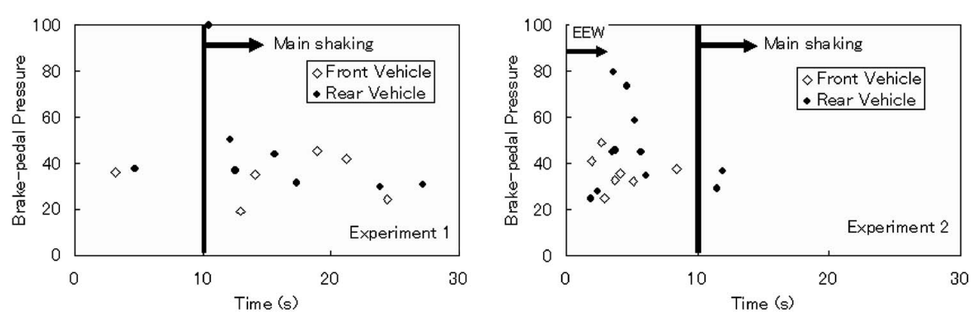

Figure 10. Maximum brake-pedal pressure and associated time in Experiments 1 and 2.

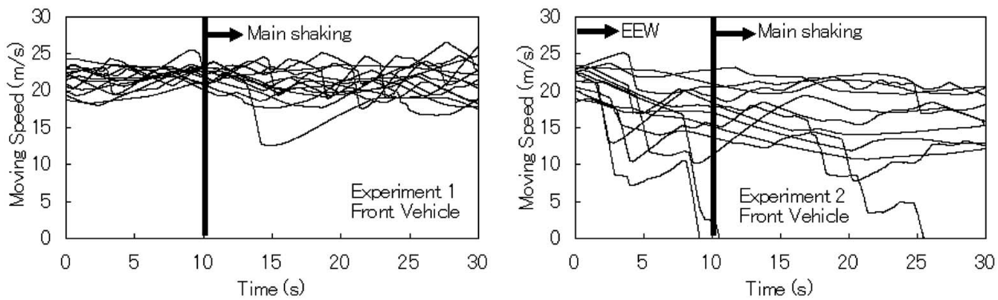

Figure 11. Comparison of moving speed in Experiments 1 and 2 (Front vehicle).

had occurred (see Figure 6). On the other hand, the test subjects in Experiment 2 began gradually reducing speed after receiving the EEW. If problems on the road surface ahead are generated by the strong ground motion, drivers operating at lower speeds are able to avoid traffic accidents more easily. Based on these results, it is evident that an EEW can be effective in improving driving safety under these circumstances.

Figure 12 shows the distance between the two vehicles in Experiments 1 and 2. As was expected from the results in Figures 10 and 11, the distance between the two cars remains unchanged in Experiment 1, while in Experiment 2, many of the rear drivers work to maintain their distance from the vehicle ahead after receiving the EEW announcement (t=5 s) because they know an earthquake is coming soon.

So far, we have discussed and compared the results of Experiment 1 (where no EEW was given to either vehicle) and those of Experiment 2 (where the EEW was given to both vehicles). However, as has been noted in previous sections, if an EEW is broadcasted by radio, some drivers on an expressway will receive it, while the others may not. Experiment 3 was set up to simulate that condition.

Figure 13 shows the distance between the two vehicles in Experiment 3, in which the EEW was only provided to the first vehicle. Here it can be seen that in some cases, the distance between the two vehicles becomes shorter during the EEW announcement (t =0−5 s). This occurs because the drivers of the front vehicle automatically begin reduc-

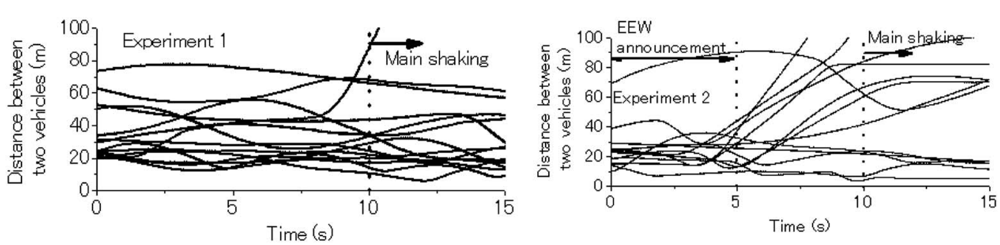

Figure 12. Distance between the two vehicles in Experiments 1 and 2.

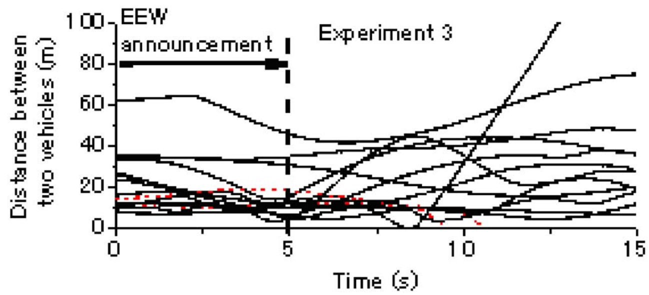

Figure 13. Distance between the two vehicles in Experiment 3. Two traffic accidents were caused and those results are shown by dashed lines.

ing speed upon receipt of the EEW, while the driver of the rear vehicle continues to drive normally. Two test subject pairs out of a total of 14 (dashed lines in Figure 13) suffered simulated crashes because of this information gap. Additionally, there were some cases where the distance between the two cars became dangerously narrow.

Figure 14 compares a chronological log of vehicle speeds and brake-pedal pressure for the test subjects in Experiments 2 and 3. When the EEW was received by both drivers (Experiment 2), the drivers of the front vehicle reduced speed by releasing the accelerator pedal instead of applying the brake pedal. The rear vehicle drivers then applied brakes as needed to maintain a proper distance from the front vehicle because both drivers knew that an earthquake was coming and were working to avoid accidents. On the other hand, the two pairs of test subjects in Experiment 3 that suffered accidents did so because the test subjects in the front vehicle applied brakes in the time after the EEW was received but before the S-wave arrival (t=10 s). And even though the test subjects in the rear vehicle tried to stop, they could not do so in time.

The above discussion illustrates how traffic accidents might occur when an EEW is issued to the general public. The information gap, which refers to the fact that some drivers will receive the EEW while others will not, can be expected to result in different driving behaviors on the expressway. As one countermeasure against the gap, activating the vehicle's hazard lights upon receiving an EEW is expected to be effective. During Experiment 3, four test subjects in the front vehicle turned on their hazard lights before reducing speed. In those cases, the rear vehicles were able to respond properly even though they had not received the EEW because the intentions of the front vehicle to reduce speed were clearly conveyed to the rear vehicle by the hazard lights. This confirms that use of hazard lights after receiving an EEW can be an effective way of warning other drivers to be on the lookout for an unknown hazard (earthquake) when driving on an expressway.

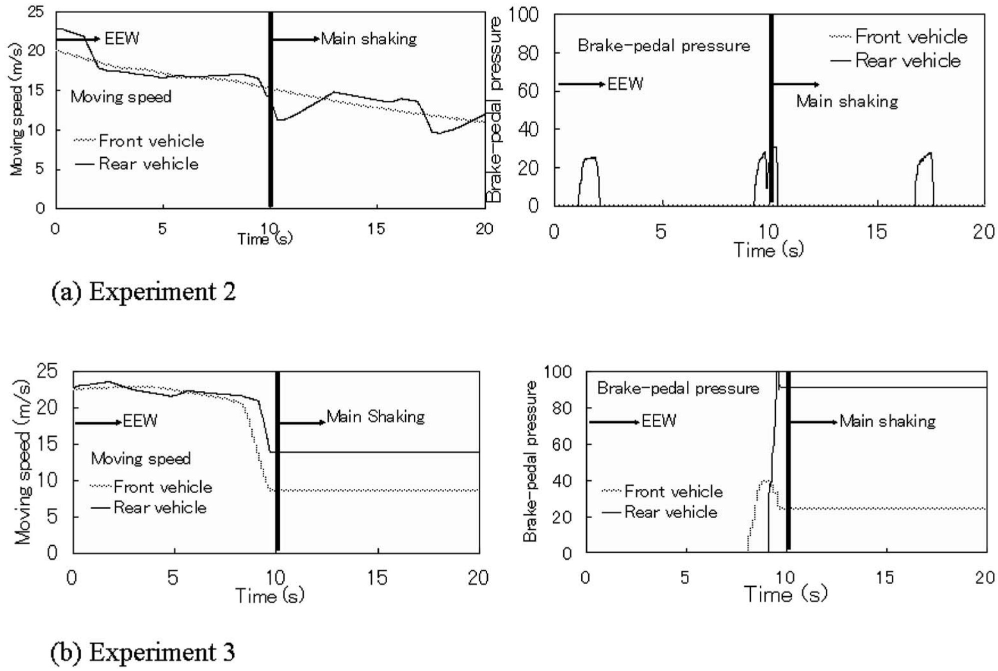

Figure 14. Example of time histories of moving speed and brake-pedal pressure in (a) Experiments 2 and (b) 3. The example of Experiment 3 shows the result of the collision from behind.

CONCLUSIONS

In this study, a series of virtual driving tests were conducted to observe the reactions of drivers under earthquake early warning (EEW) conditions. Three driving simulators, connected by a server, were employed to simulate various EEW reception conditions. Although only the driver's physical response to the receipt of an EEW alert were investigated in this study, a number of investigations have already been conducted on the perception of alerts and human behavior in general, and the JMA has conducted a variety of experiments on the reactions of TV and radio audience members to EEW messages.

According to the results of the questionnaire survey conducted after the driving experiments, many of the test subjects only recognized the abnormal vibration as an earthquake after an EEW had been received. If road embankment failures or road surface disruptions occur due to an earthquake, drivers who are unaware of the earthquake occurrence may drive directly into the damaged areas, while drivers who receive advanced warning of the impending earthquake occurrence by EEW can avoid such accidents. Thus it is felt that the EEW system can provide effective safety improvements in that regard.

Currently, EEWs transmitted to the general public via radio and TV broadcasts will not be received by all drivers, and when an EEW is only received by a portion of a group of vehicles operating in close proximity, differences in driver reactions could result in traffic accidents. This type of anticipated event actually occurred during our experiments using three driving simulators connected by a server. It was found that activation of hazard lights by the drivers that received an EEW was an effective way to warn those other drivers, who had not received the EEW, to prepare for unexpected hazards. This indicates that is important that drivers be instructed to activate their hazard lights prior to reducing speed should they receive an EEW while driving on an expressway.

Via their homepage, the JMA has recently begun working to educate the public on the proper responses to take should an EEW be transmitted. Drivers who receive an EEW transmission should not slow down suddenly. Instead, they should first activate their hazard lights in order to alert other drivers, and then they should slow down gradually before pulling safely over to the road shoulder and stopping. In order to make effective use of EEW, it will be important for people to learn the appropriate actions they should take to protect themselves.

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