SEISMIC BEHAVIOUR OF VEHICLES ON HIGHWAY

J. Kiyono(1), K. Fukunaga(2), R. Mabuchi(3), K. Shinohara(4)and T. Ito(5)

(1) Professor, Graduate School of Engineering, Kyoto University, kiyono.junji.5x@kyoto-u.ac.jp
(2) Master Student, Graduate School of Engineering, Kyoto University, fukunaga.kenji.38m@st.kyoto-u.ac.jp
(3) Master Student, Graduate School of Engineering, Kyoto University, mabuchi.ryotaro.33n@st.kyoto-u.ac.jp
(4) Engineer, Engineering Department, Hanshin Expressway Company Limited, masatsugu-shinohara@hanshin-exp.co.jp
(5) Engineer, Engineering Department, Hanshin Expressway Company Limited, takafumi-ito@hanshin-exp.co.jp

Abstract

This study focused on seismic response of vehicles running on a highway during an earthquake. Previous studies pointed out that when an earthquake occurs, probability on collisions of vehicles becomes high. We proposed brake and handle operation model and clarified how the vehicle performance under the seismic excitation. The objective of this study is to develop car-collision model on the experiment results about vehicle-to-vehicle and vehicle-to-wall collisions taking into account the brake and handle operation of drivers. The model can express collisions with non-linear spring, and it can reproduce the experiment results accurately.

A large earthquake along Nankai-trough in Japan could come with high probability of 70-80% within next 30 years. Therefore enough attentions should be paid to the occurrence of severe damage to various infrastructures. Since highway is one of the most important infrastructures, the traffic disruption should be avoided. When such severe earthquake shaking actually occur, the trouble of transportation route cause not only the logistic disruption due to the traffic accidents but also a delay of emergency response. The influence of earthquakes on running vehicles and the countermeasures to avoid such accidents have to be considered in advance.

On highway, the traveling vehicle adjusts the relative colocation with the preceding vehicle to form a stable traffic flow. In addition to the normal car-following behavior, we have to take into account brake and handle operations based on the judgment of the driver.

A six degrees-of-freedom vehicle model with translational and rotational motions of each directions is used. The brake operation model was constructed by using the results of driving simulator experiments. The handle operation model considering the influence of the ground motion transmitted from the road surface to the tire has been examined. Vehicle collisions are characterized by retaining rigidity in the early stages of collision and allowing deformation to absorb energy after reaching its maximum load. The vehicle collisions are reproduced by non-linear spring.

We proposed brake and handle operation model and clarified how the vehicle performance under the seismic excitation affects. Collision simulations were done and the damage of the car and structures caused by the accident has been verified. With this collision model, it became possible to grasp detailed situations on highway after collisions between vehicles and collisions with the side wall during earthquakes.

Keywords: seismic behavior of vehicles; car-following model; brake and handle operations; early warning; collision

1. Introduction

Probability of large earthquake such as the coming Nankai-trough earthquake, Japan, is extremely high, therefore sufficient attentions should be paid to the occurrence of severe accidents of vehicles on a highway. When such severe accidents actually occur, not only the damage of the accident itself but also the trouble of transportation route cause a delay of emergency response. The affect of earthquakes on running vehicles and the countermeasures to avoid such accidents have to be considered in advance.

This study conducted seismic response analysis of the vehicles running on the highway during an earthquake. Previous studies pointed out that collision between vehicles and bump into a sidewall may occur due to the strong shaking of the earthquake. We here develop car-collision model and handle operation model based on the results of past experiments about vehicle-to-vehicle and vehicle-to-wall collisions. The model can express collision phenomena with non-linear spring, and it can reproduce the experiment results accurately.

On a highway, running vehicles adjust the relative colocation between the preceding vehicles to form a stable traffic flow. During an earthquake, in addition to the normal following behaviour, it is necessary to grasp the disturbance of vehicle behaviour due to seismic motion and the avoidance behaviour based on the judgment of the driver.

The purpose of this study is to clarify how individual vehicle behaviour affects traffic flow by integrating the car-following model revised by the authors [1, 2, 3], the handle operation model and the collision model newly proposed here. In addition, the collision behaviour was simulated and the damage of the car and structures caused by the accident has been verified. In this paper, we focused on the construction and verification of the collision and handle operation models.

2. Analysis Model

2.1 Vehicle model

The modeling of the vehicle follows the pioneer works by Maruyama et al. [4, 5]. The longitudinal, lateral and vertical directions of the vehicle are x-, y- and z-axis, respectively. A six degrees-of-freedom vehicle model with translational and rotational motions of each directions is used. In Fig. 1, the lower spring represents the tire stiffness, and the upper spring represents the suspension spring. The upper mass, m_2, represents the mass of the vehicle body, and the lower mass, m_1, represents the wheel mass. Equations of motion are expressed as below.

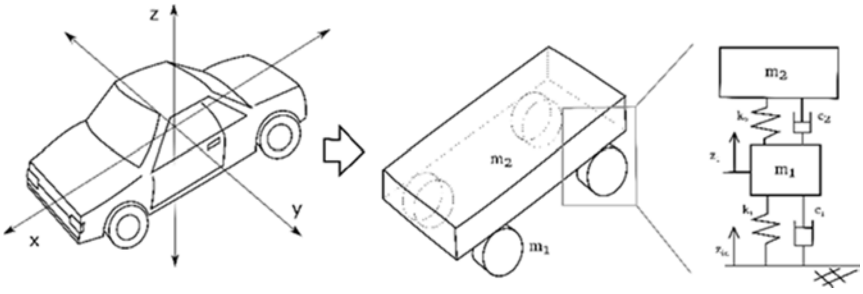


Fig. 1 – Vehicle model (after Maruyama et. al [2])

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

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

$$m_1\left(\ddot{\zeta}_{i1} + \ddot{z}_{in}\right) + c_{i1}\dot{\zeta}_{i1} + c_{i2}\left(\dot{\zeta}_{i1} - \dot{\zeta}_{i2}\right) + k_{i1}\zeta_{i1} + k_{i2}(\zeta_{i1} - \zeta_{i2}) = 0 \quad (i = 1\sim 4) \tag{3}$$

$$m_2\left(\ddot{\zeta}_{g2} + \ddot{z}_{in}\right) + \sum_{i=1}^{4} c_{i2}\left(\dot{\zeta}_{i2} - \dot{\zeta}_{i1}\right) + \sum_{i=1}^{4} k_{i2}(\zeta_{i2} - \zeta_{i1}) = 0 \tag{4}$$

In Eqs. (1) and (2), u is the x-axis velocity, v is the y-axis velocity, r is the yaw angular velocity, m is the vehicle inertial mass, and δ is the steering angle. $\ddot{x}$ and $\ddot{y}$ are accelerations caused by earthquakes in the X and Y directions in the absolute coordinate system, respectively, and ψ represents the vehicle's yaw angle. F_{xij} is the driving / braking force acting on the tires, and F_{yij} is the lateral force acting on the tires. The index i represents the front and rear wheels of the tires, and j represents the left and right of the tires. F_{Xin} and F_{Yin} represent external forces due to collisions etc. applied to the vehicle body. In Eqs. (3) and (4), z_{in} is the vertical displacement input from the road surface, and ζ_{ij} is the relative displacement of the mass j *(1~2)* with respect to the ground at the tire position i *(1~4)*. c_{ij} and k_{ij} represent the spring constant and damping coefficient of the tire *($j = 1$)* or suspension *($j = 2$)* at the tire position i, respectively.

2.2 Car-following model considering earthquake motion

Several car-following models are popular and widely used in the field of transportation engineering. A basic type is to add the positive or negative driving force to synchronize the running speed with front car. We here used the newly develop car-following model [6] which can be adaptive to the case during an earthquake.

$$m_i \cdot \ddot{x}_i(t) = (1 - \alpha)(F_{i1} + F_{i2}) + \alpha F_{i3} \tag{5}$$

$$F_{i1} = a_1(|\dot{x}_i(t)| - a_2)(|\dot{x}_i(t)| - a_3)\dot{x}_i(t) \tag{6}$$

$$F_{i2} = \sum b_i(r_{ij})\frac{x_{ij}}{r_{ij}} + \sum c_i(r_{ij})\frac{v_j - v_i}{M_c} \tag{7}$$

$$F_{i3} = \frac{a}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{(t-\mu)^2}{2\sigma^2}\right) \tag{8}$$

$$x_{ij} = x_j(t) - x_i(t) \tag{9}$$

$$r_{ij} = \left|x_{ij}\right| \tag{10}$$

In which index i and j indicate the following and preceding vehicle, respectively. F_{i1} is a driving force, F_{i2} an interaction force between two vehicles; the first term of the right side is an attraction force between vehicles and the second term is a grouping force. F_{i3} is a deceleration force due to brake operation when the driver is under the earthquake shaking. A weight, α (0-1), is the coefficient that expresses the degree of driver's emergency level. It is a function of braking strength of the driver in this study.

2.3 Handle operation model

In this study, the handle operation model considering the influence of the ground motion transmitted from the road surface to the tire has been examined. In general, the model that is forcibly given displacement and the body yaw angle by external input regardless of the road surface condition is used for the simplest model. However, in the event of an earthquake, the force transmitted from the road surface to the tire has a great influence on the vehicle's running. Therefore, grasping the vehicle behavior that is changed depending on the force should be given priority to examine the effects of an earthquake.

In actual vehicle operation, the directions of tires are changed by steering. The direction of the force acting on the tire changes, then the force determines the traveling direction of the vehicle. The force varies depending on the road surface and the vehicle body condition. The effects of seismic motion can be taken into account by modelling a series of processes of this steering operation. Therefore, in this study, the handling model has been created with reference to the emergency steering operation [7]. The following assumptions for drivers were adopted to create the model.

1. Predict future vehicle behavior and operate the handle to reduce the difference from the target vehicle behavior
2. Based on past driving experience, have the relationship between steering angle and vehicle behavior.
3. Predict the vehicle behaviour after 0.8 seconds (predicted time) and operate the handle every 0.5 seconds (steering cycle)

For Assumption 2, the relationship between steering angle and vehicle behaviour is expressed by

$$\delta(t) = K\theta'(t) + T\dot{\theta}'(t) \tag{11}$$

$$\theta'(t) = \theta_i(t + T_e) - \theta_n(t) \tag{12}$$

where δ is the steering angle, θ_i is the target yaw angle, θ_n is the yaw angle of the vehicle, T_e is the predicted time, and K and T are constants. The target trajectory y_i during changing a car's course is approximated by a trigonometric function, which is expressed by the following Eq. (13). Furthermore, the target yaw angle can be obtained from Eq. (14). Fig. 2 shows a schematic diagram of the target trajectory.

$$y_i(\mathrm{t}) = \frac{A}{2}\left(1 - \cos\left(\frac{\pi x(t)}{v_0 T_h}\right)\right) \tag{13}$$

$$\theta_i(t) = \tan^{-1}\left\{ \frac{\pi A}{2 v_0 T_h} \sin\left(\frac{\pi x(t)}{v_0 T_h}\right) \right\} \tag{14}$$

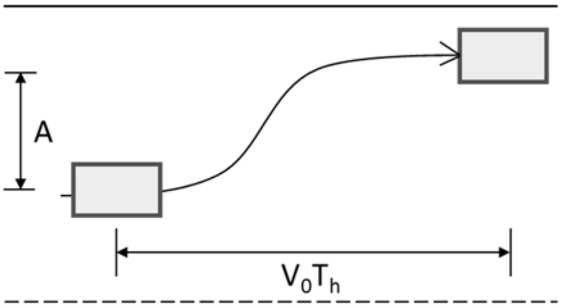


Fig. 2 – Target trajectory of vehicle

where *A* is the path change distance in the direction perpendicular to the direction of travel, v_0 is the initial speed, *x* is the travel displacement in the direction of travel during handling action, T_h is the handle operation time.

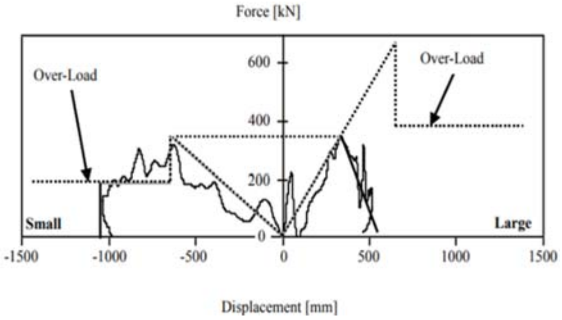


Fig. 3 – Results of vehicle frontal collision experiment relationship (Displacement-Load relationship: after Makita [8])

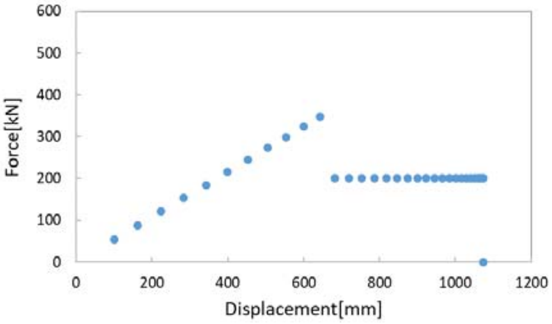


Fig. 4 – Modeled displacement-load for vehicle collision analysis

2.4 Collision model

Vehicle collisions are characterized by retaining rigidity in the early stages of collision and allowing deformation to absorb energy after reaching its maximum load. Referring the method for analyzing collision phenomena at high speeds by proposed by Furukawa et al. [8], vehicle collisions are reproduced by non-linear spring. Based on the vehicle frontal collision experiment by Makita [8], the spring characteristics were determined, and reproduction analysis was done. Fig. 3 and Fig.4 show the results of the experiment and analysis, respectively. The point, where the load change is negative in the analysis result, is 1,050mm, and it is almost the same as about 1,100mm in the experiment. The point where the load starts to decrease from 200kN in the load time history is also about 70ms and the analysis result is 68ms, which means that this analysis can be performed with high reproducibility.

3. Vehicle Behavior Analysis

3.1 Collision with side-wall

By using the proposed vehicle collision model, the vehicle behavior bumping into the side wall was analyzed.

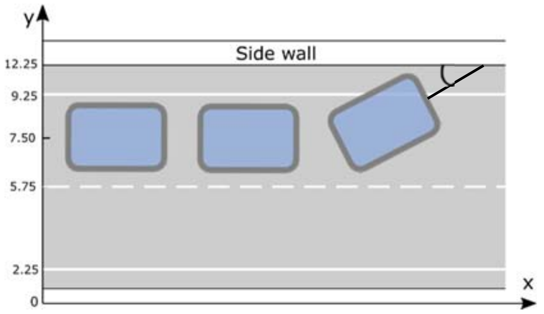


Fig. 5 – Coordinate of roadway (7.50m: center of driving lane)

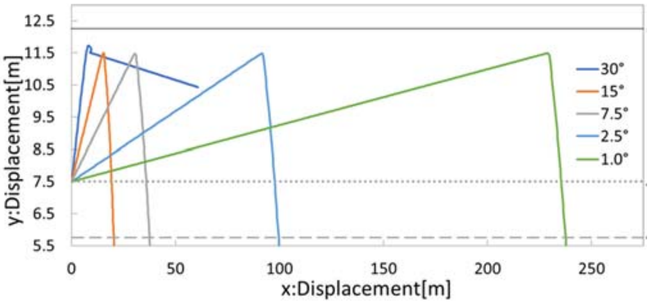


Fig. 6 – Vehicle reaction when vehicle collided with side wall in various angles (20m/s)

Consider the vehicle running on the highway with two lanes in one direction and colliding with a side wall as shown in Fig. 5. In case of relatively large collision angle of 30 degree the vehicle stays in the driving lane because of the large energy absorption, however, in case of less angle than 15 degree the vehicle rebounds to the overtaking lane exceeding the driving lane because of less energy absorption (Fig. 6).

Fig. 7 shows the impulse in the various conditions of the vehicle speed and the collision angle. Fig. 8 shows the maximum load in each condition. The collision angle in this paper is defined as the angle between the side wall and the vehicle running direction. When the collision angle was less than 15 degrees, the energy absorption was small, and the vehicle bounced with keeping its speed. On the other hand, 15 degree of the collision angle is considered as general on highway because of the high speed of vehicles. From the figure, it can be seen that when the collision angle is small or the velocity is small, the energy absorption is small and the collision is more elastic. In other words, in these cases, the possibility of causing secondary collisions such as invading the overtaking lane and colliding with other vehicles will increase.

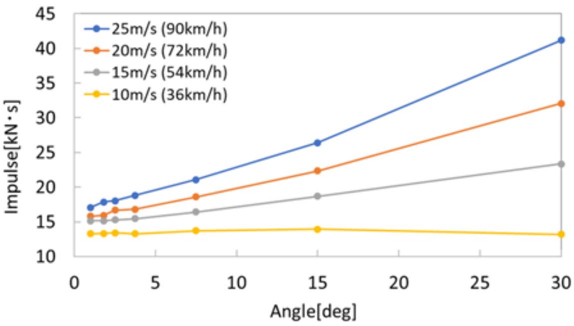


Fig. 7 – Impulse during side wall collision

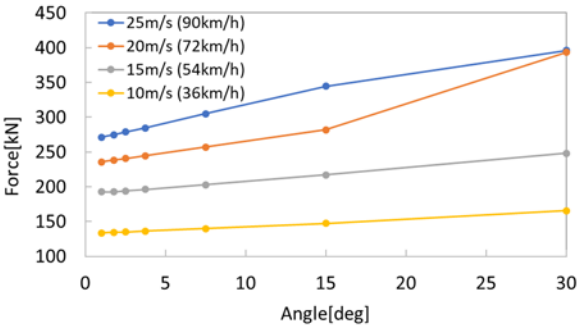
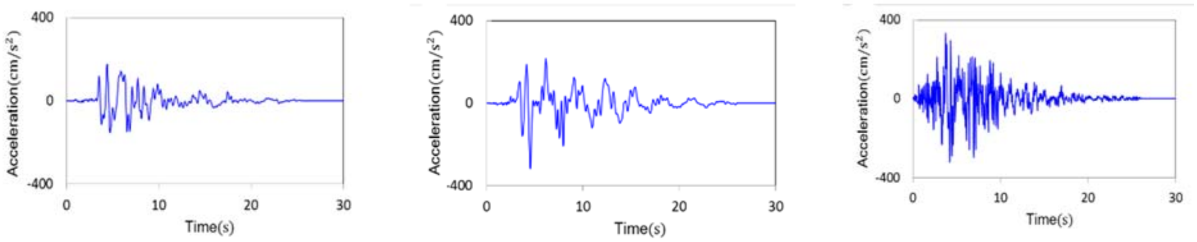


Fig. 8 – Maximum load at the time of side wall collision

3.2 Effect of handle operation under earthquake excitation

In this section, the effects of the steering wheel on the vehicle during the earthquake using the handle operation model have been examined. The acceleration data of the 1995 Hyogoken Nanbu earthquake (Kobe earthquake: Fig. 9) was input to the bridge model, and the response of the vehicle running on the bridge model is examined. Fig. 10 shows the vehicle trajectory when changing the course with a width of 3.5m as x-y plane, and Fig. 11 shows the differences of displacement in the perpendicular direction at that time during the earthquake from the normal condition.



(a) x-direction (longitudinal)　(b) y-direction (transversal)　(c) z-direction (up-down)

Fig. 9 – Input ground acceleration (1995 Kobe Earthquake: scaled)

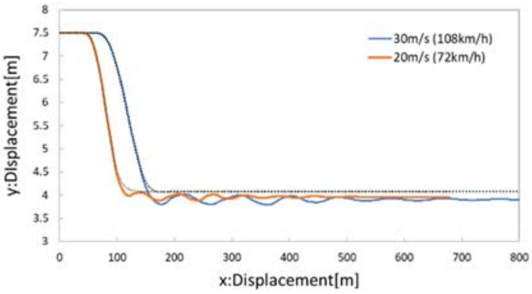


Fig. 10 – Vehicle trajectory when changing course

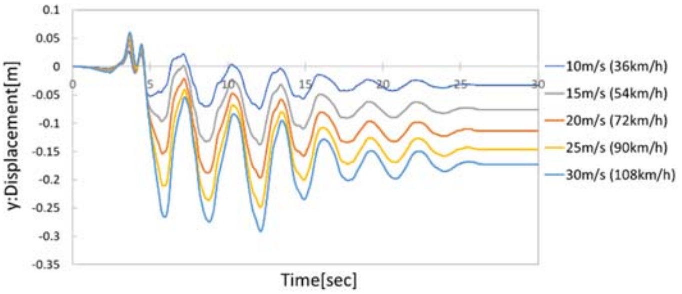


Fig. 11 – Displacement from original course

As a result, it was found that the maximum difference of distance from the normal condition was 0.3m. In other words, even if an ideal handling operation was performed at each point, the vehicle was shaken due to an earthquake, which could not be expected to the driver. And it indicated that the risk of collisions with other vehicles and structures could increase. In addition, when the driver changed the course, the shake becomes larger than when maintaining straight travel with handling.

4. Conclusions

In this paper, the handling model and the collision model has newly been proposed, and analysis of the behavior of vehicles traveling on highway during earthquakes was done. The results obtained in this study are as follows.

(1) Drivers' handling operation has been modelled as a human-vehicle system incorporating human prediction mechanism and force transmission through steering to direction change. With this model, it became possible to consider the influence of handling operation to the vehicle behavior during an earthquake.

(2) Even if ideal steering wheel operation was performed both keeping straight and changing the course, a maximum displacement of about 0.3 m was measured. The displacement when changing the course becomes larger than the displacement when keeping straight.

(3) The collision model against the other vehicle and the side wall has been proposed. It was verified based on the results of the collision experiment done by past research. With this collision model, it became possible to grasp more detailed state on highway after collisions between vehicles and collisions with the side wall during earthquakes.

(4) The collision analysis on the side wall in various condition of vehicle's speed and collision angle, revealed that it bounced with keeping its speed in collision angles considered to be general on highway. The result suggested the possibility of a collision with another vehicle after the collision with the side wall could be increase.

5. Acknowledgements

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