Dynamic Response of High-Speed-Moving Vehicle Subjected to Seismic Excitation Considering Passengers' Dynamics

A. Shintani, T. Ito, C. Nakagawa & Y. Iwasaki
Osaka Prefecture University, Japan

SUMMARY:
The vibration behavior of the vehicle considering the dynamics of the passengers subjected to seismic excitation is investigated. The one-vehicle model which consists of a body and two trucks and four wheel sets is constructed. Based on the derived model, the vehicle is excited by actual earthquake wave in horizontal and vertical directions simultaneously by numerical simulation. The response behaviors of the vehicle are investigated for several seismic inputs by using the risk rate of rollover. Furthermore, by constructing the simple passengers' model and incorporating that with the vehicle model, the effects of the passengers' dynamics on the vibrational behavior of the vehicle subjected to the earthquakes are investigated.

Keywords: vehicle, rollover, passenger, earthquake

1. INTRODUCTION

Recently the running speeds of the railway vehicles become very high. When the high-speed running vehicles derail or rollover, many people may die or be injured, and large damage is given to the traffic and transportation systems. The high-speed railway TGV in France derailed in 1992 and 1993. The high-speed railway ICE in Deutschland derailed in 1998. On the other hand, recently, large-scale earthquakes occurred and the derail or rollover incidents of railway vehicles occurred in Japan. For example, many railway vehicles derailed in the Hyogo-Nambu Earthquake in 1995. The high-speed running Shinkansen derailed in Niigata Chuetsu Earthquake in 2004.

Then it is important to investigate the vibrational behavior of the high-speed running vehicle subjected to base excitation such as an earthquake. Kunieda et al. (1981) investigated the risk rate of rollover of the railway vehicle subjected to an earthquake in the horizontal direction based on the modal analysis. Miyamoto et al. (1998) reported the vibrational behavior of the railway vehicle subjected to sinusoidal excitations in horizontal and vertical directions based on the fifty eight degrees of freedom vehicle model. Matsumoto et al. (2003) investigated the vibrational behavior of the vehicle running on the structure subjected to an earthquake. Yang and Wu (2002) studied the dynamic stability of moving trains over bridges subjected to an earthquake. However, the responses of such vehicles subjected to huge earthquakes have not been investigated enough. On the other hand, authors (2008) have researched the seismic response of the high-speed-moving vehicle based on the relatively simple half-vehicle model which consists of half body, truck and wheel set.

Furthermore, weight saving of the vehicles proceeds for speeding up. Passengers' weight accounts for a large portion of the total weight of the vehicle. Hence, it is considered that the effect of the passengers including passengers' dynamics on the vibration behavior of the vehicle becomes important. Therefore, we began to investigate the seismic response of the vehicle considering the passengers' dynamics based on the one-vehicle model (2012).

In this paper, we investigate the vibration behavior of the vehicle considering the dynamics of the passengers subjected to seismic motion. One-vehicle model consists of a body and two trucks and four wheel sets. A passenger is modeled by two degrees of freedom model. Using the risk rate of rollover, the behavior of the high-speed-moving vehicle without passengers is investigated. Furthermore, the behavior of the vehicle considering passengers' dynamics is also investigated. The effect of the passengers' dynamics on the vibrational behavior is considered.

2. METHOD OF ANALYSIS

2.1. Vehicle Model

The analytical model of vehicle used in this paper is shown in Figs.2.1 and 2.2. Figure 2.1 shows the vehicle model from the anterior view on the curve rail track (*y*-*z* plane). Figure 2.2 shows the overhead view of the vehicle model on the straight rail track (*x*-*y* plane). The vehicle consists of one body, two trucks and four wheel sets. Body and trucks are connected by springs and dampers in the longitudinal, horizontal and vertical directions. Trucks and wheel sets are also connected in the same way. Rails and the ground are combined. Body, trucks and wheel sets are assumed to be sufficiently rigid. As the results, the vehicle model is given by 21 DOFs system. The parameters of the vehicle are determined by supposing the Shinkansen Series 200 (Tanifuji, 1986).

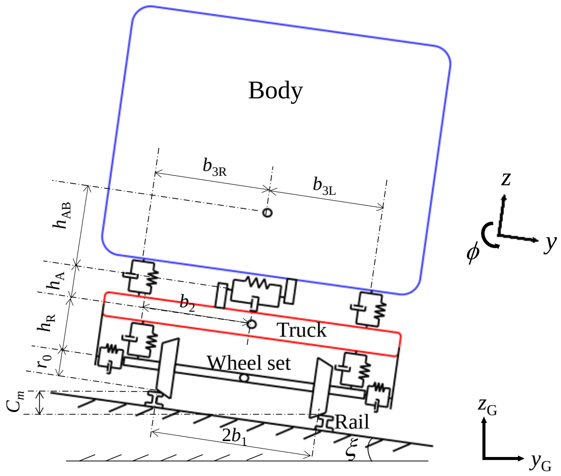


Figure 2.1. Analytical model of one vehicle (*y*-*z* plane)

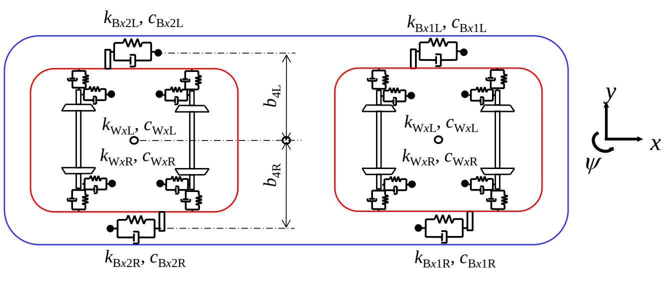


Figure 2.2. Analytical model of one vehicle (*x*-*y* plane)

When the vehicle is subjected to the earthquake, the relative displacements of the springs in the analytical model become large. Then it is considered that the stopper works to reduce the larger relative displacement. To consider the effect of the stopper, some springs in Fig.2.3 are modeled as the nonlinear springs as used in the former paper (2008). In this paper, the destruction of the stopper is not considered. The forces acting between the wheel sets and rails are considered as the creep forces as also used in the former paper (2008).

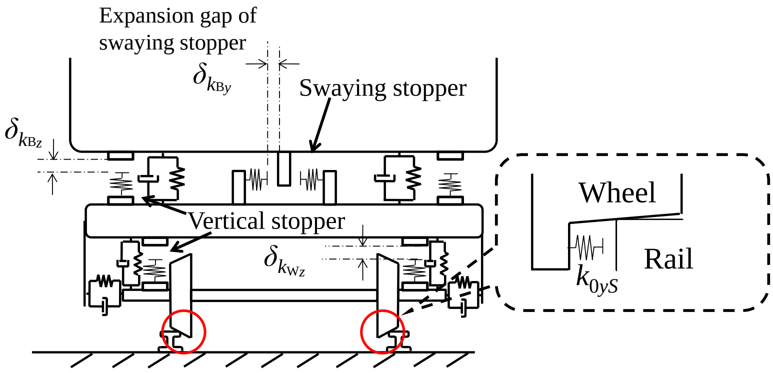


Figure 2.3. Model of stoppers

2.2. Passengers' Model

The passenger's model is considered as a totally two degrees of freedom system, that is, the passenger vibrates in one degree of freedom in each of horizontal and vertical direction. Modeling of the passengers' properties in vertical directions is based on the parameters by Tohtake's experimental results (1973) using the actual railway vehicle seats. Furthermore, we performed the experiment in the horizontal direction and determined the eigenfrequency and the damping ratio in horizontal direction. Analytical parameters per unit passenger are shown in Table 2.1.

Table 2.1. Parameter values of passenger model

Item	Parameter	Value
Mass of a passenger	m_p	65 [kg]
Natural frequency in horizontal direction	f_{py}	1.15 [Hz]
Damping ratio in horizontal direction	ζ_{py}	0.48
Natural frequency in vertical direction	f_{pz}	5.37 [Hz]
Damping ratio in vertical direction	ζ_{pz}	0.22

Passengers are modeled by eight sets of mass, springs and dampers and the passengers are arranged at eight points on the body symmetrically in horizontal and longitudinal directions as shown in Fig.2.4. Spring constants and damping coefficients are determined by making each eigenfrequency and damping ratio coincide with eigenfrequency and damping ratio of one passenger, respectively.

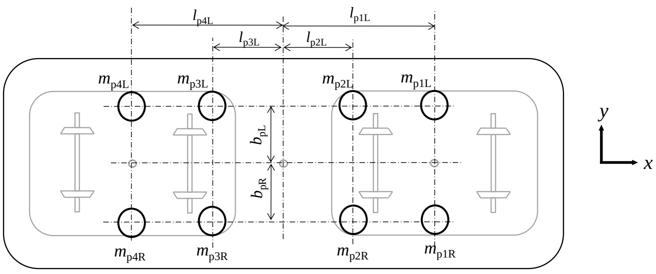


Figure 2.4. Position of passengers

From the above consideration, the equations of motion of body, trucks, wheel sets and passengers are given by Lagrangian equations of motion as follows:

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F\}, \tag{2.1}$$

where $[M]$, $[C]$, $[K]$ are mass, damping, stiffness matrices, respectively, $\{X\}$ is the displacement vector of body, trucks, wheel sets and passengers, $\{F\}$ is the acting force vector.

2.3. Risk Rate of Rollover

We employ the risk rate of rollover (Kunieda, 1981) indicating the dangerousness of rollover of the vehicle. As shown in Fig.4, the risk rate of rollover is defined as the following index. The index evaluates the dangerousness of rollover by judging whether or not the total force vector acting on the vehicle including gravitational force, centrifugal force, inertia force passes inside of the intersection of the rail track and the wheel set. In this paper, the risk rate of rollover is calculated by the equivalent ratio of wheel load decrease. Letting jth wheel loads from the front in right and left sides be P_{Rj}, P_{Lj} (j=1, 2, 3, 4), respectively, the rate of wheel load decrease in jth wheel set is given by

$$D_j = \frac{P_{Lj} - P_{Rj}}{P_{Lj} + P_{Rj}}. \tag{2.2}$$

The risk rate of rollover for total one vehicle D is defined as the mean value of all the risk rates at four wheel sets:

$$D = \frac{D_1 + D_2 + D_3 + D_4}{4}. \tag{2.3}$$

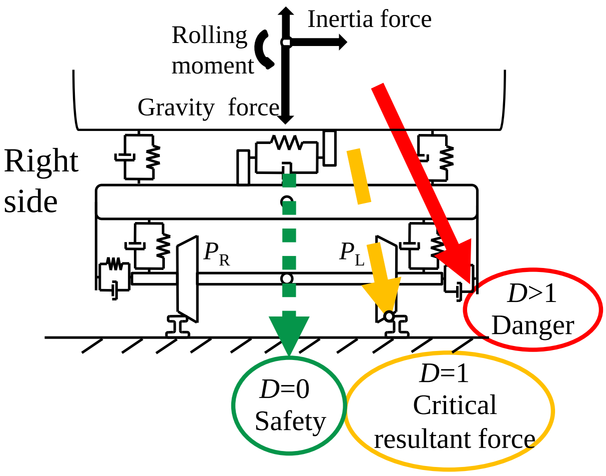


Figure 2.4. Forces and moments acting on body, truck and wheel set

3. NUMERICAL SIMULATION

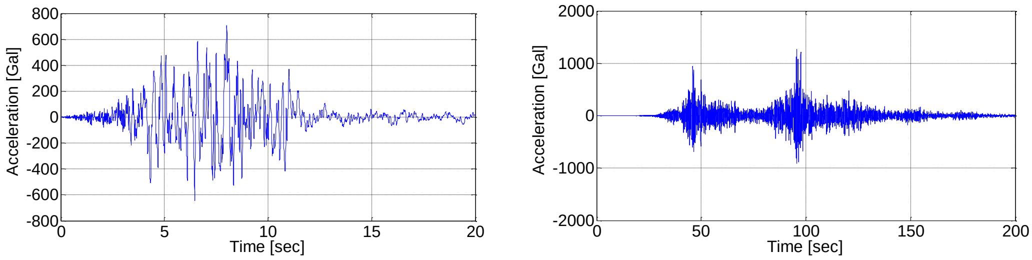
3.1. Analytical Condition

Important natural frequencies of the vehicle with or without stoppers are listed in Table 3.1. We assume that passengers are one hundred persons. In this case, passengers' weight is 15% of the body weight.

Table 3.1. Natural frequencies (or periods) of high-speed-running vehicle

	mode	without stoppers frequency (Hz)	(period) (s)	with stoppers frequency (Hz)	(period) (s)
Horizontal directions	1st	0.57	1.74	1.35	0.74
	3rd	0.93	1.08	3.45	0.29
Vertical directions	1st	1.09	0.92	2.50	0.40
	3rd	6.67	0.15	11.76	0.085

Niigata Chuetsu Earthquake measured at Nagaoka Branch and Tohoku-chiho Taiheiyo-oki Earthquake measured at Tukidate in East-west and vertical directions are employed as the input seismic wave (K-NET). Acceleration waves in East-west direction of these earthquakes are shown in Fig.3.1(a), (b). Maximum value of acceleration of Tohoku-chiho Taiheiyo-oki Earthquake (1269 Gal) is larger than that of Niigata Chuetsu Earthquake (705.9 Gal). Duration time of Tohoku-chiho Taiheiyo-oki Earthquake is longer than that of Niigata Chuetsu Earthquake. Niigata Chuetsu Earthquake has wider spectral range of period than that of Tohoku-chiho Taiheiyo-oki Earthquake. Acceleration response spectra for these earthquakes are shown later.

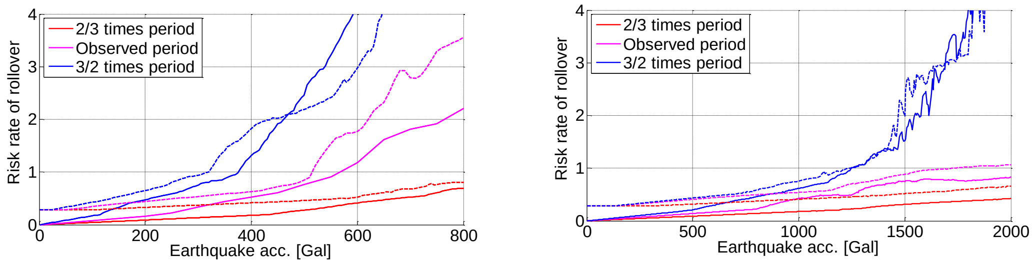


(a) Niigata Chuetsu Earthquake (b) Tohoku-chiho Taiheiyo-oki Earthquake

Figure 3.1. Acceleration of earthquakes (East-west direction)

3.2. Behavior of the Vehicle without Passengers

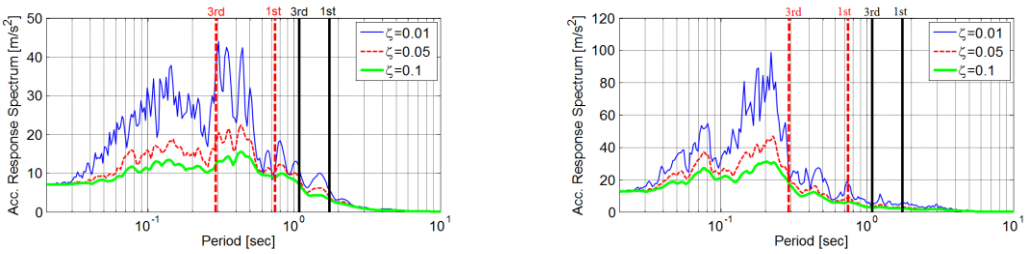
We consider the difference between the risk rates of rollover of the vehicle running on the straight and curve rail tracks. Running speed is set as 255 km/h. The curvature radius of the curve rail track is 2500 m, the cant is set as 200 mm. Input waves are given by varying the acceleration amplitude in east-west and vertical directions of observed Niigata Chuetsu Earthquake and Tohoku-chiho Taiheiyo-oki Earthquake. The effect of the maximum acceleration amplitude on the maximum risk rate of rollover is shown in Fig.3.2. Fig.3.2(a), (b) show the maximum risk rate of rollover for Niigata Chuetsu Earthquake and Tohoku-chiho Taiheiyo-oki Earthquake, respectively. In each figure, the solid and dashed lines imply the risk rates for straight rail track and for curve rail track, respectively.



(a) Niigata Chuetsu Earthquake (b) Tohoku-chiho Taiheiyo-oki Earthquake

Figure 3.2. Effect of acceleration amplitude and predominant period on the risk rate of rollover (solid line: straight rail track, dashed line: curve rail track)

In case of Niigata Chuetsu Earthquake, as the maximum acceleration amplitude increases, the risk rate increases. The maximum risk rate increases rapidly when the maximum acceleration exceeds the constant earthquake acceleration. This is because the constant earthquake acceleration is the limit value where the stopper works. Comparing the risk rates of the vehicle running on the straight and curve rail tracks, the risk rate on the curve rail track is larger than that on the straight rail track for smaller acceleration amplitude. This is because the directions of the centrifugal force and the inertia force are same and the rollover moment in case of the curve rail track is larger than that in straight rail track. In case of Tohoku-chiho Taiheiyo-oki Earthquake, the same tendency holds.



(a) Niigata-ken Chuetsu Earthquake (b) Tohoku-chiho Taiheiyo-oki Earthquake

Figure 3.3. Response spectra for observed earthquakes and natural periods of the vehicle with and without stoppers (East-west direction)

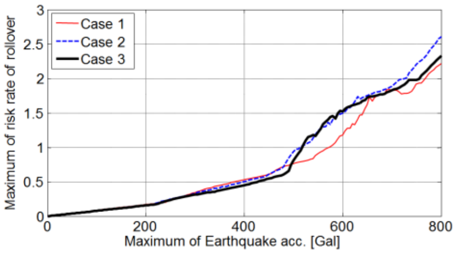
The effect of the predominant frequency (or predominant period) on the risk rate of rollover is investigated. Here, earthquake waves with lower and higher predominant frequencies are produced by 1.5 times expanding or 2/3 times shortening the time axis of original earthquake.

In case of Niigata Chuetsu Earthquake, the effects of the predominant period of earthquake waves on the risk rate of rollover are also shown in Fig.3.2(a). The predominant frequency of the long period (i.e., low frequency) of Niigata Chuetsu Earthquake is about 1.47 - 2.22 Hz (0.45 - 0.68 s in period), that in short period (i.e., high frequency) earthquake is about 3.33 - 5.00 Hz (0.20 - 0.30 s in period), that in observed earthquake is about 2.22 - 3.33 Hz (0.30 - 0.45 s in period). Acceleration response spectrum for observed Niigata Chuetsu Earthquake and natural periods of the vehicle with and without stoppers are shown in Fig.3.3(a). As the predominant frequency of the earthquake wave becomes low, that is the predominant period becomes long, the risk rate of rollover increases. The first mode natural frequency of the vehicle without stopper is about 0.57 Hz (1.74 s in period) as shown in Table 3.1, and is close to the predominant frequency of the earthquake wave when the predominant frequency of the earthquake becomes small. Therefore, the vibration amplitudes of the body, the trucks and the wheel sets become large. As a result, the vehicle tends to contact with the stopper. Hence, the first mode natural frequency of the vehicle increases and it coincides with the predominant frequency of the earthquake wave. Thus, the vibration amplitudes of the vehicle become larger more and more. For these reasons, the risk rate of rollover increases.

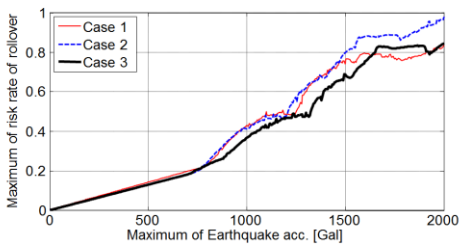
In case of Tohoku-chiho Taiheiyo-oki Earthquake, the effects of the predominant period of earthquake waves on the risk rate of rollover are also shown in Fig.3.2(b). The predominant frequency of the long period (i.e., low frequency) of Tohoku-chiho Taiheiyo-oki Earthquake is about 3.03 - 3.84 Hz (0.26 - 0.33 s in period), that in short period (i.e., high frequency) earthquake is about 6.25 - 7.14 Hz (0.14 - 0.16 s in period), that in observed earthquake is about 4.55 - 5.56 Hz (0.18 - 0.22 s in period). Acceleration response spectrum for observed Tohoku-chiho Taiheiyo-oki Earthquake and natural periods of the vehicle with and without stoppers are shown in Fig.3.3(b).In this case, the same tendency holds. However, the risk rate for Niigata Chuetsu Earthquake is larger than that for Tohoku-chiho Taiheiyo-oki Earthquake since the value of the spectrum of Niigata Chuetsu Earthquake at the natural frequency is larger than that of Tohoku-chiho Taiheiyo-oki Earthquake.

3.3. Effect of Passengers' Dynamics on the Vibrational Behavior

The effect of the passengers' dynamics on the risk rate is considered. We consider three cases: Case 1; considering only vehicle, Case 2; regarding the passengers as the mere mass increment, Case 3; considering passengers’ dynamics. The risk rates of rollover of the vehicle running on the straight rail track at the velocity of 255 km/h subjected to earthquakes are shown in Fig.3.4. In Fig.3.4(a), the risk rate for Case 2 is larger than that for Case 1. The similar tendency holds for Case 2 and Case 3. The behaviors of Case 2 and Case 3 are different for large earthquake acceleration. In Fig.3.4(b), the risk rates for Case 1 and Case 2 have similar tendency. The behaviors of Case 1 and Case 2 are different for large earthquake acceleration. And, the risk rate for Case 3 is roughly smaller than that for Case 1 and Case 2. In Figs.3.4(a), (b), the vibrational behaviors of three cases differ especially after the stopper works. It depends on the character of the earthquake, whether or not the risk rate when considering passengers’ dynamics is larger than other case. Therefore, it is important to consider the passengers’ dynamics when the behavior of the total vehicle-passenger system is investigated correctly. The difference among three cases is not so large in this simulation. In this case, the passengers are one hundred and the passengers’ weight is 15% of the vehicle body weight. However, the recent vehicle weight is lighter than that used in this simulation. Then, the ratio of the passengers’ weight to the vehicle body weight becomes higher.



(a) Niigata Chuetsu Earthquake

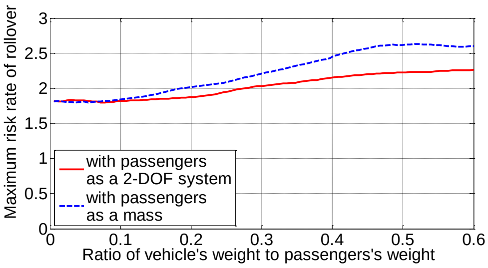


(b) Tohoku-chiho Taiheiyo-oki Earthquake

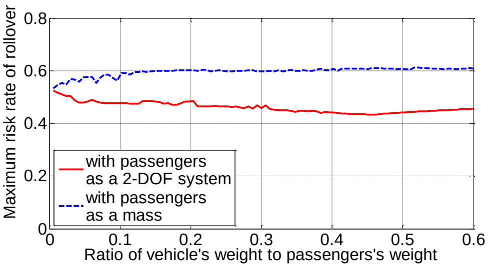
Figure 3.4. Effect of passengers' dynamic characteristics

3.4. Effect of Numbers of the Passengers on the Vibrational Behavior

We analyze the vibrational behavior of the vehicle by changing the rate of the passengers' weight to the vehicle body weight. We consider the case where the vehicle runs on the straight rail track at the velocity of 255 km/h subjected to seismic wave. The effects of the rate of passengers’ weight on the risk rate of rollover are shown in Fig.3.5. When the ratio of the passengers' weight becomes large, the influence of the passengers' dynamics on the risk rate becomes large in the both of Figs.3.5(a) and (b).



(a) Niigata Chuetsu Earthquake



(b) Tohoku-chiho Taiheiyo-oki Earthquake

Figure 3.5. Effect of the number of passengers

Since the weight saving of the vehicle will be promoted in future, it is important to consider passengers' dynamics in the vibration analysis.

4. CONCLUSIONS

Dynamic behavior of the high-speed running vehicle subjected to an earthquake considering the passengers' dynamics is investigated by using the risk rate of rollover. It is found that the swaying stopper, the acceleration amplitude, the predominant period of the seismic wave and passengers' dynamics give very large influences on risk rate of rollover.

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