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SAFETY ANALYSIS OF VEHICLES RUNNING ON BRIDGE DURING AN EARTHQUAKE

R. R. Parajuli(1)*, J. Kiyono(2) and H. Yatsumoto(3)

(1) *Doctoral student, Graduate School of engineering, Kyoto University, Japan, parajuli.ram.27z@st.kyoto-u.ac.jp*
(2) *Professor, Graduate School of engineering, Kyoto University, Japan*
(3) *Hanshin Expressways Company Limited, Japan*

Abstract

This study mainly focused on seismic response analysis of highway vehicles during the earthquake running on the elevated structure. Elevated structures those mainly dominated in city expressways and highways in mountainous areas; seismic response of such structures is spatially varied with type and properties of structures. Actual earthquake acceleration that excites the vehicle running on it, depends on the location where the response of structures subjected at that particular time. Local soil condition of the surrounding area play a role in vehicle excitation when they are running on the ground but that difference might be negligible in comparison with the structural response. Virtual symmetrical cable-stayed bridge of length 1330 m is considered in the study with a central span of 580 m between two central towers. Kobe and El Centro earthquake ground motions are selected for structural analysis. Nodal responses on deck level are calculated using finite element analysis of the model. Input earthquake motion for seismic response analysis of the vehicle is calculated through interpolation of nodal responses of the structure at deck level. Location of the respective vehicle that depends on speed and its' origin is the base of the interpolation. Lagrange's three-point formula is used as the data follows simple parabolic function in between three points for interpolation. Interpolated earthquake accelerations are shown for the cases of different origin and speeds. Frequency and the amplitude of interpolated earthquake motions are varying with the origin and speed. Vertical response of the vehicle is calculated using two degrees of freedom system of quarter vehicle model. Seismic responses of vehicle in lateral and longitudinal directions are calculated using circular path and linear momentum (CPLM) method. Magic Formula Model (MFM) is considered on determining the tyre forces acting in the vehicle. Passenger car, bus and truck are used in the study as different types of vehicles. We consider the ideal condition of vehicle running on the bridge that driver's reaction is not taking in to account for this study on controlling the vehicle. Single vehicle model running through the bridge analyzed for the cases of different speed and the origin. Speeds of the vehicle ranging from rest condition to the 30.0 m/sec are analyzed for all three types of vehicles when the origin of the vehicle is starting of the bridge. Lateral displacements are increased with the ascending value of the speed in all types of vehicle when the earthquake motion was used from El Centro earthquake, In contrast with this trend, response of vehicles for Kobe earthquake is almost in descending order but very small in quantity. When the origin of the vehicle changed from start of the bridge to the last point of the bridge with the constant speed of 20 m/sec for all cases, lateral displacements of the vehicles follows the different trend. Vehicle response for the cases of vehicle position within bridge and exit from the bridge during shaking, affect on the result.

Keywords: earthquake motion for vehicle; Interpolation; CPLM method; seismic response analysis; vehicle risk

1. Introduction

Risk of drivers on losing control of their vehicle during a strong earthquake is more complex, involving mechanical, physical, and psychological factors. This risk depends on the individual's driving skills, their physical and psychological abilities, and on the mechanical properties of the vehicle. The effect of the earthquake on a driver of a moving vehicle during an earthquake may be negligible when the ground motion is small, as the vehicle itself is in motion. However, large shaking may tend to push the vehicle laterally or longitudinally, causing the driver to lose control of the vehicle. Drivers' responses and the characteristics of the ground motion during the 1983 Nihon-kai-chubu earthquake (M7.7) in Akita prefecture and the 1987 Chiba-ken-oki earthquake (M6.7) in Chiba prefecture, both of Japan Meteorological Agency (JMA) seismic intensity V were studied using a questionnaire survey [1]. The survey revealed that about 50% of drivers felt the earthquake motion as the vehicle and their surroundings displayed unusual behavior and movement. Most of the drivers stopped their vehicles because they felt they were in danger. The survey also found that steering instability was felt in directions both longitudinal and lateral to the car while driving the vehicles. A similar study after the 2003 Miyagiken-Oki earthquake (M7.0) found a relationship between the JMA intensity of the earthquake and the drivers' recognition of the event and their driving response to it [2]. Video[3] during the long period Gorkha earthquake 2015[4] in Kathmandu shows the responses of parked vehicles, where the vehicles are moving significantly during the shaking. Vehicle toppling risk also revealed after The 2016 Kumamoto earthquake on April 16th, 2016. Six cars and a truck parked on the parking area got toppled during the main shock of M7.3 earthquake[5].

City expressways are dominated by elevated structures rather than surface road. Hanshin expressway in Japan is of total about 250km in length comprises of about 80% of steel and concrete bridges, another about 10% of surface road and rest 10% of tunnel structures standing to complete the network. Earthquake ground motion that propagates through the ground surface will be different in the road surface where it passes via bridges or viaducts depending on structural response. Seismic response analysis of vehicle considering earthquake ground motion would not be enough explaining the real scenario of vehicle behavior for elevated structures.

We are considering a model of a cable-stayed, symmetrical bridge having total length of1330 m. Dynamic analysis of the bridge with input ground motion in base of piers had given nodal acceleration response in bridge deck. Interpolation of nodal acceleration for each vehicle in each time step of calculation gives input ground motion for each vehicle which depends on the location of it. To analyze the vehicle's response to seismic motion, it was modelled with six degrees of freedom. The equation of motion was used as the basic equation for the analysis of the response of the tyres and the car body as well as the transformation of the acceleration from the road surface to the vehicle. The longitudinal and lateral responses were calculated using the CPLM method that we proposed before[6] . We also considered the pitching, rolling and yawing motions of the vehicle as rotations in three directions. The forces acting on the tyres were calculated using the Magic Formula Model (MFM) [7]. The MFM coefficients were taken from the literature [8], using the trust region reflective (TRR) method algorithm.

Interpolation of the nodal responses of bridge structure for input to the vehicle has done and shown the interpolated acceleration for different cases of speed and location of the vehicle. We analyzed the responses of car, bus and truck in the longitudinal and lateral directions for several conditions using the interpolated earthquake accelerations. The relationships between the vehicle's responses with the speed and peak ground acceleration (PGA) were also investigated.

2. Bridge and vehicle modelling

A virtual cable-stayed symmetrical bridge of total length 1330 m was modeled with nodal distance of 5 m between central three nodes and 15 m in rest of part except two nodal distances of 7.5m in both sides near short piers in between long and edge piers. Central span of bridge is 580m long with three columns on each side as shown in Fig. 1. Total numbers of nodes in bridge deck level are 91. The analysis was performed using commercial software Forum 8, Engineering Studio. Dynamic analysis of bridge with input ground motion as shown in Fig. 2, in base of piers give nodal acceleration response. Nodal response accelerations of bridge model were later used in the determination of earthquake motion for analysis of vehicle behavior.

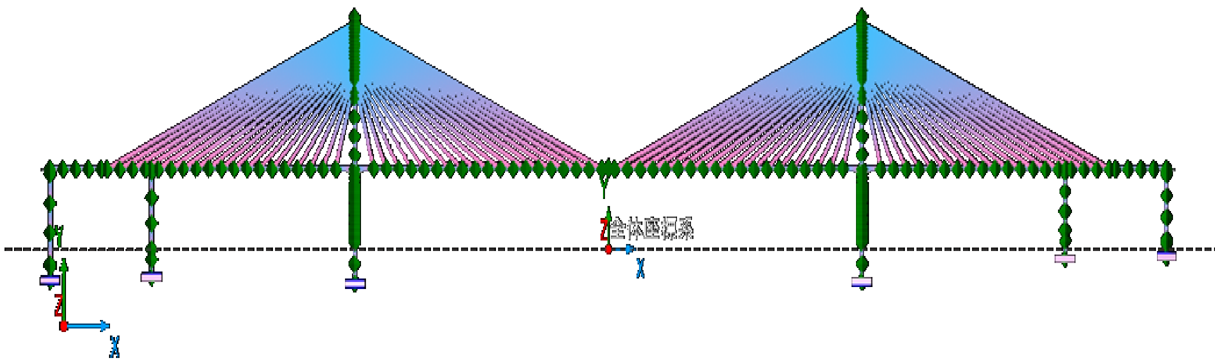

Fig. 1 – Bridge model

Vehicle model defined as six degrees of freedom system with three translational motions as well as three rotational motions. Longitudinal, lateral and vertical translational motions along with corresponding rotations as rolling, pitching and yawing motions for ‘X’, ‘Y’ and ‘Z’ axes are also taken into consideration. Vehicle model parameters were chosen from data provided by Maruyama and Yamazaki[9]. Bus and truck data are also gathered for the analysis. Mass of the vehicle body and tyre, dimensions of the vehicle and other parameters for all type of the vehicles are shown in Table 1.

Table 1 – Parameters of the vehicle models

Parameters	Symbols	Value			Unit
		Car	Bus	Truck	
Each tyre mass	m_1	25.00	41.25	41.25	*kg*
Vehicle body mass	m_2	1100.00	19490.00	24705.00	*kg*
Length between front wheel and CG	l_f	1000.00	3375.00	4585.00	*mm*
Length between rear wheel and CG	l_r	1635.00	2825.00	2595.00	*mm*
Height of CG	h_0	350.00	863.00	1000.00	*mm*
Length between right and left axel	d	1505.00	2065.00	2055.00	*mm*
Stiffness for rolling motion	$K_ø$	117.60	117.60	117.60	*kN m*
Elastic constant of steering	K_{st}	48.50	48.50	48.50	*kN m/rad*
Spring constant between tyre and ground	k_1	800.00	784.00	784.00	*kN/m*
Suspension spring constant between tyre and mass	k_2	70.00	68.60	68.60	*kN/m*
Tyre damping	c_1	0.098	0.098	0.098	*kN s/m*
Suspension damping	c_2	4.90	4.90	4.90	*kN s/m*

3. Interpolation of earthquake motion

Speed and origin of vehicle vary in each case for multiple vehicle analysis, which leads to variation of real exciting earthquake motion depends on the response of bridge where the vehicle stands at that particular time.

Hence to find out the real earthquake motion for running vehicle, interpolation of bridge response by considering three points around the location of vehicle was used. Lagrange's interpolation, considering the known three points (nodes), could find new value for new location with in this range. This form of interpolation is suitable in case of cubic or square parabolic functions. Lagrange's form of polynomial interpolation is combination of linear functions. In our case as nodal distances are maximum of 15 meters and the relation of data to three points (45 m) are seemed square parabolic functions, three point interpolation had chosen. We had checked the plot of relation of acceleration with location in some time steps, that shows there is no any sharp or uneven changes, it has square parabolic functions.

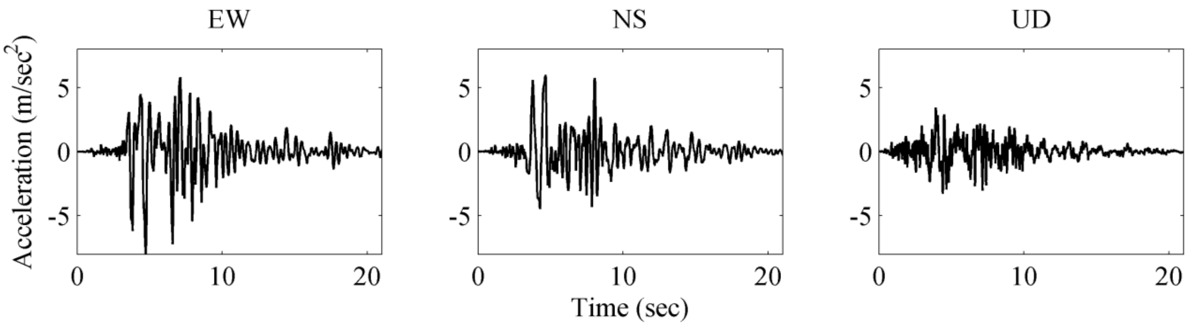

Fig. 2 – Input ground motion

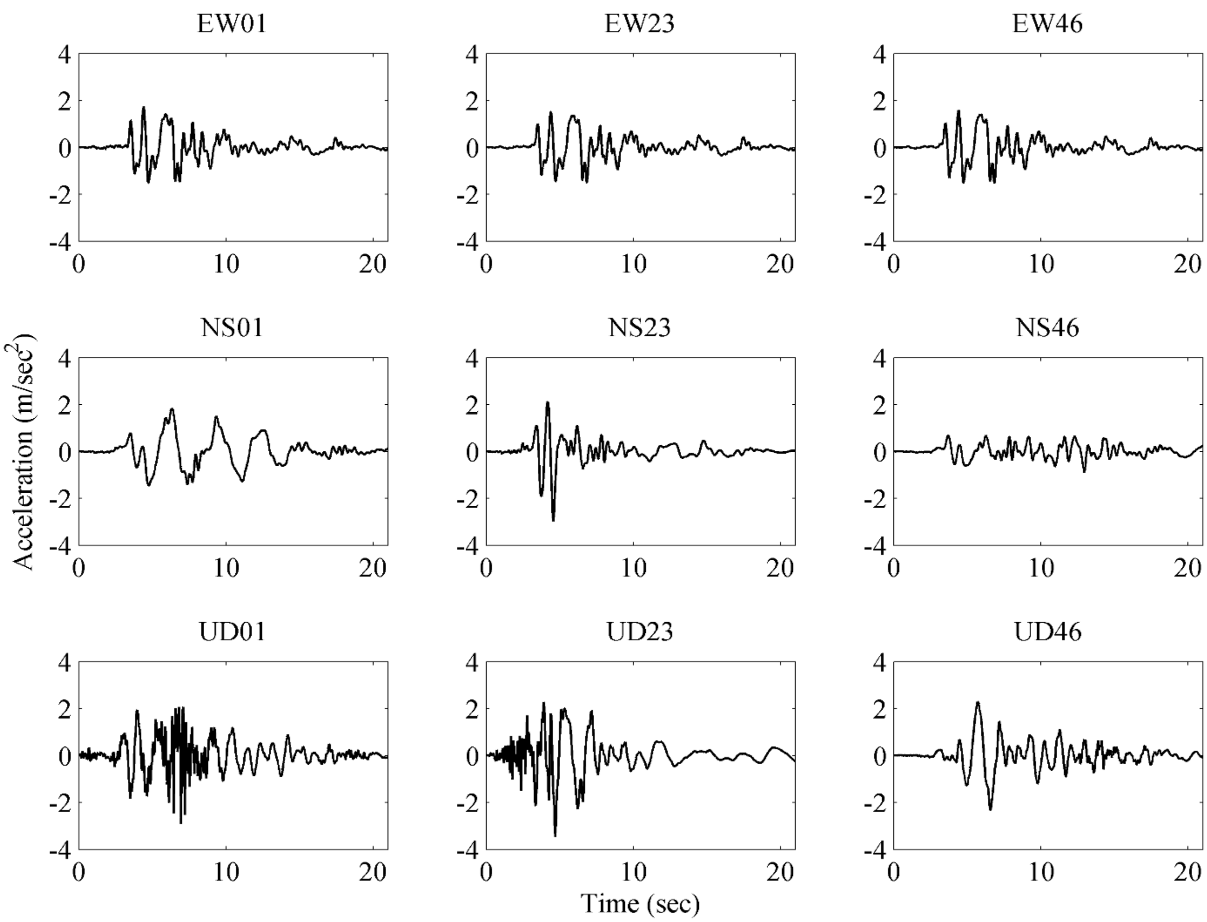

Fig. 3 – Interpolation of earthquake motion for a vehicle with speed 20 m/sec depends on location

Fig. 2 shows the input ground motion from Kobe earthquake that excites in the foundation of bridge model as shown in Fig. 1. Nodal responses at bridge deck level are listed and interpolated for the vehicle with the constant speed of 20.0 m/sec. Fig. 3 shows the interpolated acceleration when the vehicle is just entering the bridge, on quarter of the bridge and on the center of the bridge with node values 01, 23 and 46. These earthquake motions that actually excite the vehicle, varies with the location, not only in amplitude but also in the frequency of the wave. Similarly when we consider the vehicles with different running speed, originated from the same location, amplitude and frequency of the wave will be different as shown in Fig. 4. Where we show the result of interpolated wave for the vehicle at rest, with speed of 14.0 and 30.0 m/sec, assuming all the vehicles originate from same point, entry point of bridge as earthquake shaking starts.

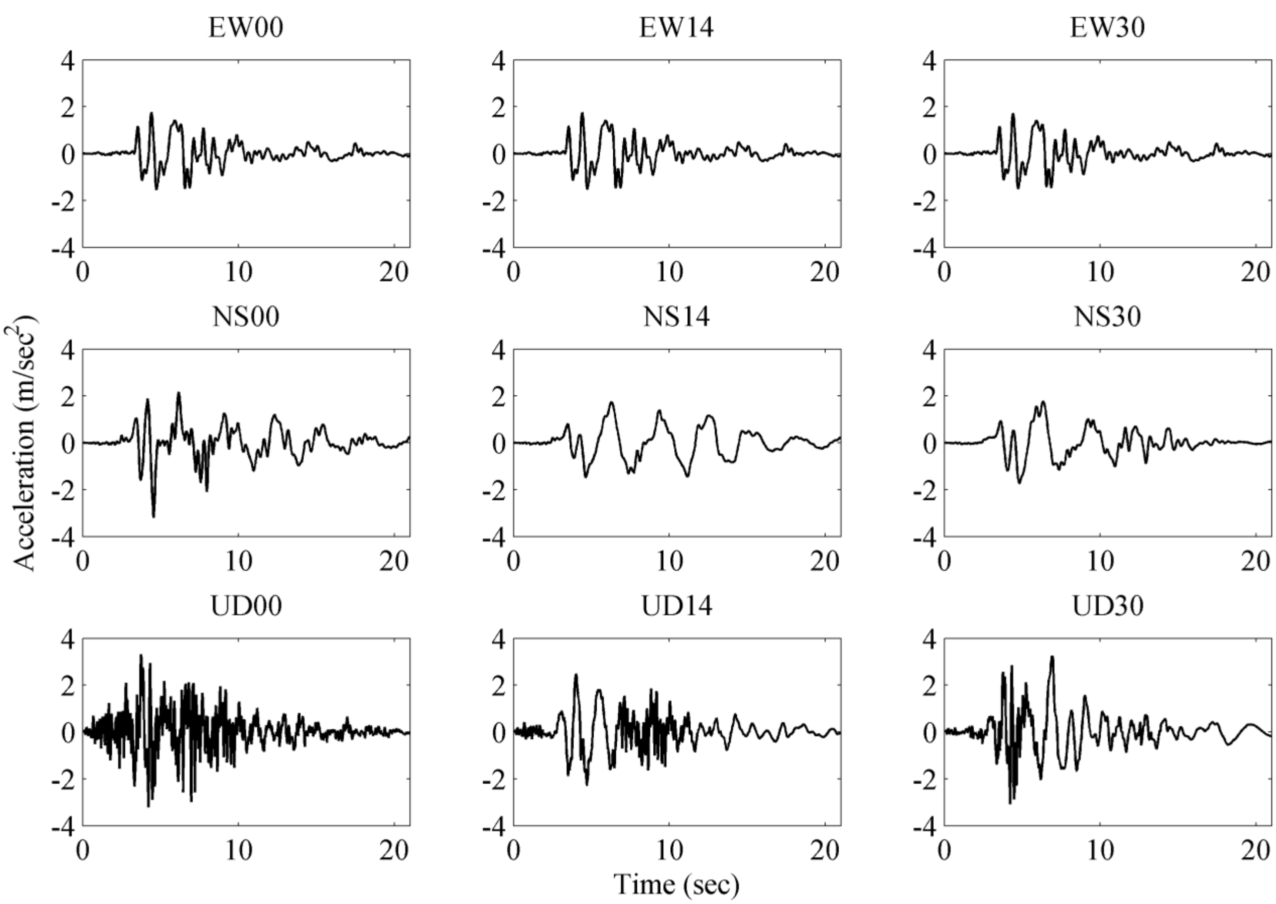

Fig. 4 – Interpolation of earthquake motion for different speed of vehicle

4. Analysis

Rolling and pitching motion of the vehicle are the rotational motions on the longitudinal and lateral axes respectively. Taking the moment of forces acted on those axes, the relationships of the forces are shown in Eq. (1) and Eq. (2).

$$(K_{\emptyset} - mgh)\emptyset = m(\dot{v} + ur)h \quad (1)$$

$$\{2K(l_f^2 + l_r^2\}\theta_p = m(\dot{u} - vr)h \quad (2)$$

Where '$K_\emptyset$' is rolling stiffness, 'K' is stiffness of the tyre,'$\emptyset$' is the rolling angle, 'θ_p' is the pitching angle, height of center of gravity (CG) of the vehicle mass is 'h', 'u' and 'v' are the longitudinal and lateral velocities of the vehicle. Yaw angular velocity is denoted by 'r', 'l_f' and 'l_r' are the distance of the front and rare axle form the CG of the vehicle mass. 'm' is the total mass of the vehicle including tyres and body.

Yawing motion of the vehicle is remaining rotational motion of the vehicle along the vertical axis, it can be define as Eq. (3). Where 'I_z' is moment of inertia of the vehicle,'d' is the length between right and left wheels. F'_y and F'_x are the lateral and longitudinal forces act on each tyre, index 1 and 2 refers to the front and rare and left and right.

$$I_z \frac{dr}{dt} = \left(F'_{y11} + F'_{y12}\right) l_f - \left(F'_{y21} + F'_{y22}\right) l_r + \left(-F'_{x11} + F'_{x12}\right) \frac{d}{2} + \left(-F'_{x21} + F'_{x22}\right) \frac{d}{2} \tag{3}$$

Vertical response of vehicle due to earthquake excitation is quite simply defined by using the two degree of freedom system. Combination of the road, tyre and car body with spring and dashpots as a quarter vehicle model is used in this study. Each tyre models with spring and dashpot connected with ground and vehicle mass modeled with spring and dashpot over the axle (suspension of vehicle). Equations of motion for the model are shown in Eq. (4) and Eq. (5). Where z_g, z_1 and z_2 are the vertical displacements of ground, relative vertical displacements of tyre and vehicle body.

$$m_1\left(\ddot{z}_1 + \ddot{z}_g\right) + c_1\dot{z}_1 + c_2(\dot{z}_1 - \dot{z}_2) + k_1 z_1 + k_2(z_1 - z_2) = 0 \tag{4}$$

$$m_2\left(\ddot{z}_2 + \ddot{z}_g\right) + c_2(\dot{z}_2 - \dot{z}_1) + k_2(z_2 - z_1) = 0 \tag{5}$$

Transformation of ground acceleration to the vehicle in longitudinal and transverse direction, we use single degree of freedom system that comprises of ground and car body. Stiffness and damping constants are used same of tyre properties that used during vertical response analysis.

External forces act on body are now determined with the transferred accelerations after transferring from global to the local coordinate. Longitudinal forces act on the vehicle are, external force exerted due to earthquake acceleration, force generated due to the slip of the tyres on the ground and the rolling resistance of tyres. Rolling resistance force (F_{roll}) is the threshold level of force that applied force needs to cross to start the vehicle. In this research we neglect the rolling resistance for the constant speed cases, where we suppose there is a constant acceleration to nullify this effect. But in case where the vehicle has to stop or where the vehicle is in rest position we consider this effect in the analysis. Coefficients of rolling resistance (C_{roll}) for concrete, asphalt road surface and the maximum steering angles of the vehicles are shown in Table 2 [10].

Table 2 – Rolling resistance coefficient

SN.	Vehicle type	Coefficient of rolling resistance	Maximum steering angle
1	Car	0.013	31.6°
2	Bus	0.01	38.7°
3	Truck	0.01	31.7°

Force acting on each tyre of vehicle, longitudinal and transverse along with self-aligning moment is calculated by using Magic Formula Model (MFM) [7] as Eq. (6) - (8) considering pure slip condition. Where *'X'* is the input variable, slip angle for lateral force and slip ratio for the longitudinal. *'Y'* is the output variable. *'B'*, *'C'*, *'D'* and *'E'* are the stiffness factors, shape factors, peak value and curvature factor respectively. These factors are calculated considering the pure slip conditions, based on TRR algorithm, that found best in compare with several algorithms [8]. Pressure acts on the tyres are calculated considering static as well as the effect of the rolling pitching and vertical motion of the vehicle [9].

$$y(x) = D\,sin\left[C\,tan^{-1}\{Bx - E(Bx - arctan(bx))\}\right] \tag{6}$$

$$Y(x) = y(x) + S_v \tag{7}$$

$$x = X + S_h \tag{8}$$

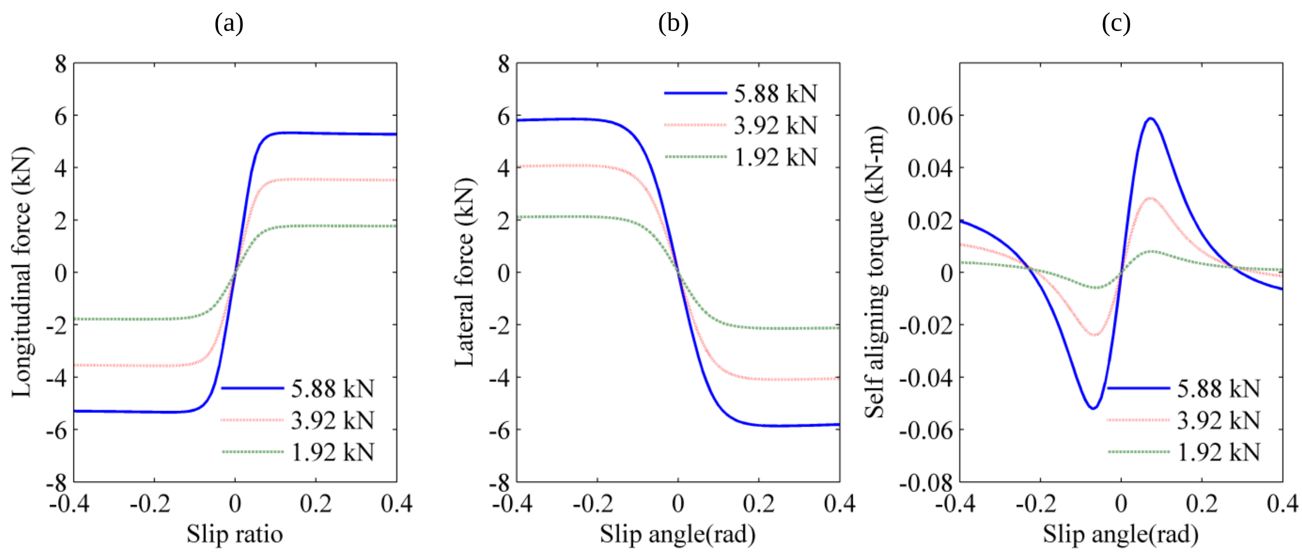

Fig. 5 – Relationship of longitudinal and lateral forces and self-aligning torque with slip ratio and slip angles using Magic Formula Model

Fig. (5a) and Fig. (5b) shows the relationship of longitudinal and lateral forces on tyres with slip ratio and slip angle respectively, for three cases of vertical loading (5.88 kN, 3.92 kN and 1.96 kN). For the same cases Fig. (5c) shows the variation of self-aligning torque with slip angles. We selected the R15 tyre, where adopted nominal load is taken as 6.15 kN.

The total longitudinal force act on the tyre can calculate by using the Eq. (9). Rolling force (F_{roll}) will always be against the moving direction. F_{xg} is the external force due to the earthquake acceleration in longitudinal direction.

$$F_x = F_{xg} + F_{xs} \pm F_{roll} \tag{9}$$

$$F_{xg} = m\ddot{x} \tag{10}$$

Lateral sliding of the tyres might occur, when the total force acting on the lateral direction summed up to some values. We find the frictional force that can withstand against the applied force considering the frictional coefficient and normal load. If the lateral force exerted on the tyres due to the earthquake (F_{yg}) is larger than frictional resistant(F_r), then vehicle will slide laterally. Here we consider the forces those act on the tyre on road surface are as shown in Eq. (11).

$$F_y = |F_{yg}| - F_r \tag{11}$$

$$F_{yg} = m\ddot{y} \tag{12}$$

Considering the principle of conservation of momentum along the vehicular axis, we could get the new velocity vector v_2 along that axis from Eq. (13). F_x is the total external force that applied during the time interval (Δt) in this system. Change in angle of vehicle steering in Δt is θ where θ_x is the angle of vehicle orientation from global longitudinal axis [6].

$$mv_1 + F_x\Delta t = mv_2 \tag{13}$$

$$v_x = v_2 \cos\theta_1 \tag{14}$$

$$v_y = \left[v_2 + \frac{F_y dt}{M}\right]\sin\theta_1 \tag{15}$$

$$\theta_1 = \theta_x + \theta \tag{16}$$

$$D_{x_i} = D_{x_{i-1}} + v_{x_i}\Delta t \tag{17}$$

$$D_{y_i} = D_{y_{i-1}} + v_{y_i}\Delta t \tag{18}$$

Velocity and the displacement of the vehicle are now calculated from the Eqs. (14) - (18), in global coordinates. The course of the vehicle is defined in each step with the summation of slip angles, using the Eq. (19).

$$\theta_{1_{i+1}} = \theta_{1_i} + \theta_i \tag{19}$$

5. Result and discussion

Vehicles of three categories, car, bus and truck are analyzed using the CPLM method[6] with interpolated earthquake excitation. We considered two variables as location of the vehicle and speed of the vehicle for two different earthquakes, Kobe and El Centro. Maximum lateral displacements for the fixed time window (time of PGA plus 5 seconds) of earthquake motion were calculated. Fig. 6 shows the results for the maximum lateral displacements with various origins in right and the left figure shows the same for cases of rest to the speed up to 30.0 m/sec in increment of 2.0 m/sec. Location of the vehicle at the time of triggering by earthquake plays a role on lateral response of vehicle. Bus is more critical on risk of misalignment than truck and car on the sides, where all of the vehicles have low level of effect on lateral movement when they are at the center of the bridge. In the case of bus, maximum lateral movement form the moving direction is more than four times when the bus is in the chainage of 0+200 meters than in the center of bridge (0+400 m to 0+600 m from entry side). Similar trend of responses are followed by the car and truck even though the values are small. Response of the vehicles seems much higher when the location during triggering of earthquake is near to the exit point due to the higher values of ground acceleration. When the vehicle exit from the bridge, it respond to the ground acceleration despite of structural response, whose PGA is much higher than that of nodal responses of bridge. Velocity of the vehicles also play a vital role along with the characteristics of earthquake motion, in general as the speed of the vehicle increases, lateral response of the vehicle is also ascending in case of El Centro but it is slightly descending for the case of Kobe when the speed crosses 4.0 m/sec.

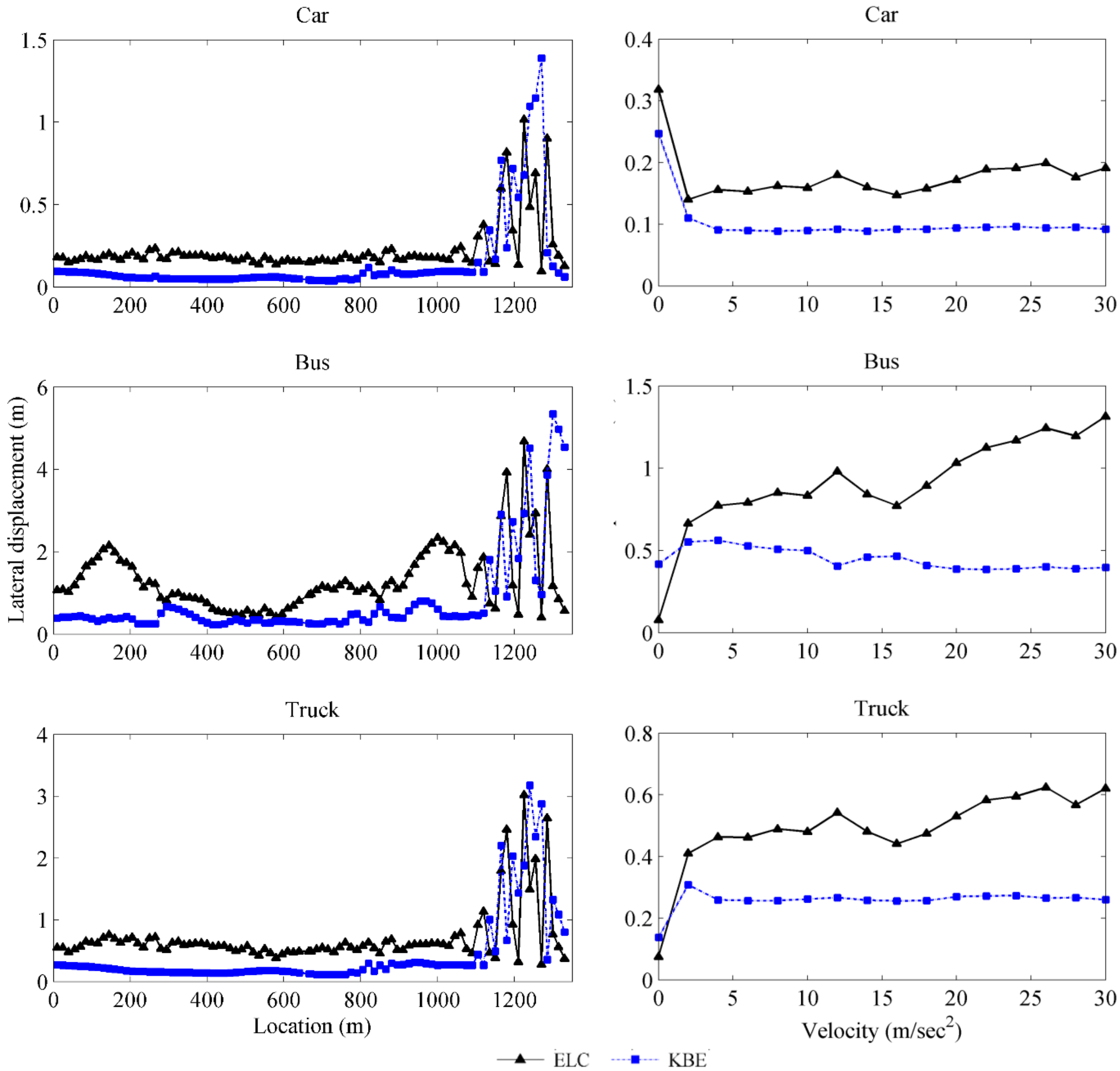

Fig. 6 – Lateral displacement of vehicles for different locations of origin and different speed

6. Conclusion

Earthquake motion to analyze the vehicle response running on the bridge or any elevated structures is essential to consider the response of the structure. Interpolation of the structural responses is useful to find the actual excitation of the vehicle due to earthquake. The speed of the vehicle determines the actual excitation that depends on the location of vehicle along the section of structure. Frequency and the amplitude of the earthquake motion are varied with the speed of the vehicle for the same structure. Vehicles running on the cable stayed bridge deck are subjected to higher risk when they are near to the entry and exit points but the same vehicle could exposed to lower risk if that will be in the center. Speed of the vehicle is also responsible on the risk of lateral deviation. Vehicles with higher speed are in more risk than that of lower in some cases like El Centro earthquake case but the trend of the maximum lateral displacements for the case of Kobe earthquake motion is almost constant, negligibly varying after the speed of 4 m/sec.

We could conclude here that the risk associated with the vehicles running on the cable-stayed bridge is depending on the location of the vehicle during the earthquake and also the speed of the vehicle. Structural and the ground motion characteristics variations are another key parameters, whose effect on vehicle risk analysis are left for the future work.

7. References

[1] K. Kawashima, H. Sugita, and T. Kanoh, "Effect of earthquake on driving of vehicle based on questionnaire survey," *Struct. Eng./Earthquake Eng.*, vol. 6, no. 2, pp. 405–412, 1989.

[2] Y. Maruyama and F. Yamazaki, "Relationship Between Seismic Intensity and Drivers' Reaction in the 2003 Miyagiken-Oki Earthquake," *Struct. Eng. / Earthq. Eng.*, vol. 23, no. 1, p. 69s–74s, 2006.

[3] "CCTV footage during Gorkha earthquake - YouTube," 2015. [Online]. Available: https://www.youtube.com/watch?v=I20dIt88-u4.

[4] R. R. Parajuli and J. Kiyono, "Ground motion characteristics of the 2015 gorkha earthquake, survey of damage to stone masonry structures and structural field tests," *Front. Built Environ.*, vol. 1, no. 23, 2015.

[5] R. R. Parajuli, J. Kiyono, and Y. Okumura, "TOPPLED VEHICLES DURING KUMAMOTO EARTHQUAKE : RESPONSE ANALYSIS & PGA ESTIMATION IN NEAR FAULT ZONE," in *35th annual meeting of Japan Society for Natural Disaster Science*, 2016, pp. 23–24.

[6] R. R. Parajuli and J. Kiyono, "Circular Path and Linear Momentum Method for Seismic Response Analysis of Vehicles," *Front. Built Environ.*, vol. 2, no. 16, 2016.

[7] H. B. Pacejka, *Tyre and Vehicle Dynamics*. 2006.

[8] A. V. Alagappan, K. V. N. Rao, and R. K. Kumar, "A comparison of various algorithms to extract Magic Formula tyre model coefficients for vehicle dynamics simulations," *Veh. Syst. Dyn.*, vol. 53, no. 2, pp. 154–178, 2014.

[9] Y. Maruyama and F. Yamazaki, "Seismic response analysis on the stability of running vehicles," *Earthq. Eng. Struct. Dyn.*, vol. 31, no. 11, pp. 1915–1932, Nov. 2002.

[10] J. Y. Wong, *THEORY OF GROUND VEHICLES*, Third., vol. 1. John Wiley & Sons, 2001.