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Computer Simulation of Dynamic Interactions Between Vehicle and Long Span Box Girder Bridges

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Abstract: Moving vehicle loads, associated with roadway traffic can induce significant dynamic effects on the structural behaviours of bridges, especially for long-span bridges. The main objective of current research is to study traffic induced dynamic responses of long-span box-girder bridges. The finite element method has been employed in this study to obtain a three-dimensional mathematical model for the bridge system. For vehicle-bridge dynamic interaction analysis, the vehicle is modeled as a more realistic three-axle, six-wheel system, and the corresponding dynamic interaction equations have been derived. The bridge-vehicle interaction is affected by many factors. The current study has been focused on such factors as: vehicle speed, vehicle damping ratio, multiple traffic lanes, mass ratio of vehicle and bridge, and dynamic characteristics of bridge. Case studies have been conducted to investigate these factors by using several box girder bridge examples including Confederation Bridge, the longest box girder bridge in the world.

Key words: vibration; box girder bridge; long-span; bridge-vehicle interaction; finite element analysis

Introduction

Box-girder and deck type bridges have been proven to be very efficient structural forms for medium to long-span bridges. These bridges normally consist of interconnected plate elements of either prestressed or reinforced concrete, or structural steel, or a combination of them, which provide sufficient flexural and torsional strength to resist applied loads. Box-girder bridges are usually aesthetically pleasing and can be easily constructed to follow any required alignment in plan and require relatively small amount of maintenance.

Box-girder bridges tend to be slender and more flexible than other types of bridges. Therefore, attention must be paid to the avoidance of excessive acceleration and dynamic deflections, which may cause pedestrian's discomfort and concern. Usually, dynamic deflections are more pronounced in bridges with torsional dominant modes, especially at sidewalk locations.

Such modes tend to have more detrimental effects on human responses to vibrations and comfort level of pedestrians using the bridge[1]. The acceleration level of a bridge is also directly related to the governing vibration mode. Since acceleration has a significant effect on human sensation and pedestrian comfort, the torsional mode must be avoided at all costs.

In recent years, considerable efforts have been made in order to better understand the dynamic behavior of box girder bridges with traffic loads. In the previous studies, the vehicle has usually been modeled as: moving load, moving mass or sprung mass. Only a few researchers have adopted 3D vehicle model. Most of the previous studies focus on short to medium span box girder bridges, and little information is available for long-span box girder bridges. Some of the key parameters such as vehicle speed and dynamic properties of bridge have investigated previously; however, very

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little information is publicly available on considering more realistic vehicle models moving on multiple lanes and the effect of vehicle damping.

Therefore, the main objective of the free vibration analysis of box-girder bridges is to investigate key parameters and their effects on dynamic responses of bridges. Several box girder bridge examples including a real long span box girder bridge will be studied by using the above numerical model for their dynamic interactions. The vehicle is modeled as a more realistic three-axle, six-wheel system. A comprehensive parametric study will also be carried to investigate the key governing parameters. The finite element method has been employed in this study to obtain an analytical model for the bridge and vehicle systems. Both the natural frequencies and the dynamic response of the box-girder bridge will be assessed using this analytical model.

1 Box-Girder Bridge Modeling

Two box-girder bridges, namely Bridge A and Confederation Bridge, are considered in the present study. Bridge A, shown in Fig. 1, is 9.35 m wide and simply supported with twin steel cells equally spaced at 2.45 m and a concrete deck of 200 mm in thickness. Solid plate diaphragms of thickness 12 mm are provided at both ends of the bridge within the box in order to reduce the distortion of the boxes with a relatively low frequency. Variations of geometries for the bridge throughout this study are based on this cross section.

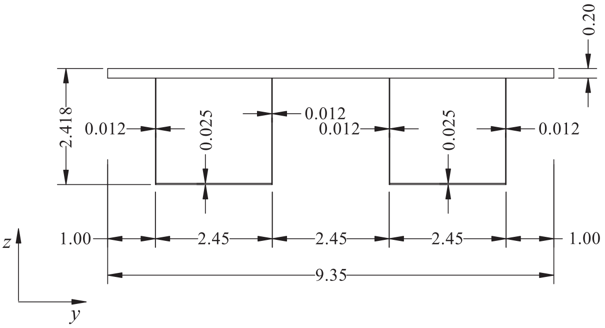


Fig. 1 Bridge A (Unit: m)

The 12.9 km long Confederation Bridge is the longest prestressed concrete box girder bridge in the world built over salt water providing a highway traffic link across the Northumberland Strait in eastern Canada[2]. The bridge consists of 11 approach spans and 45 main spans, each 250 m in length, at a typical height of 40 m above the mean sea level. For a typical main span, each two piers are rigidly connected together by the superstructure to form a portal frame of 250 m span, with a 96-m cantilever beyond each pier. Repeating these portal frames for all marine spans produces 21 frames. These frames are connected together by 60 m simply supported drop-in spans. A portal frame of the main spans is adopted in this analysis, as shown in Fig. 2. The bridge cross-section is a prestressed single cell trapezoidal box. The total width of the bridge is 12 m with 11 m roadway. The depth of the superstructure varies from 4.5 m at mid span to 14 m at the pier location. The cross section is reinforced with steel “A” diaphragm at each pier to reduce torsional vibration at lower frequencies.

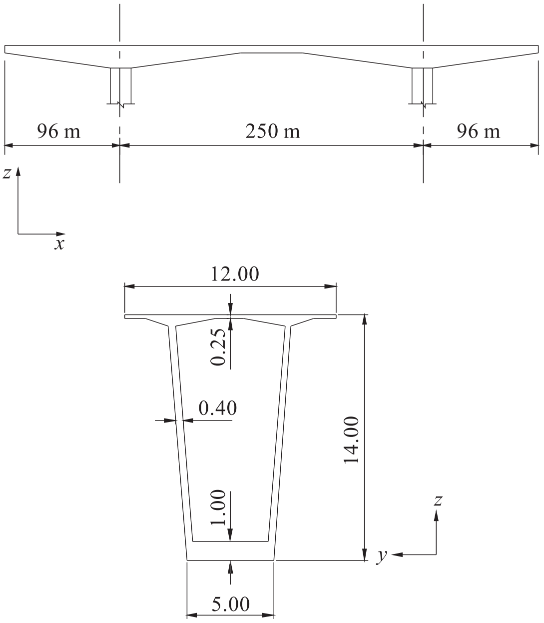


Fig. 2 Confederation bridge (Unit: m)

The bridges are discretized as 3D finite element model. The bridge decks, the box girders and the diaphragms have been modeled as 8-node flat shell element. Each nodes of shell elements incorporate six degrees of freedom, i.e., translation in the x, y, and z directions as well as rotation about the x, y, and z axes.

2 Vehicle Modeling

For the vehicle-bridge dynamic interaction analysis, the vehicle is modeled as a three-axle, six-wheel system as shown in Fig. 3. The vehicle body consists of a tractor and a trailer, which are considered to be rigid and supported by a system of springs and dash-pots attached to the three axles. The trailer with concentrated mass m_2 is pin connected to the tractor with concentrated mass m_1 at point D. The dash-pots provide viscous damping. The mass of the axles, wheels, driveshaft, brakes, and the suspension system is supported by the wheels, which always remain in contact with the bridge surface.

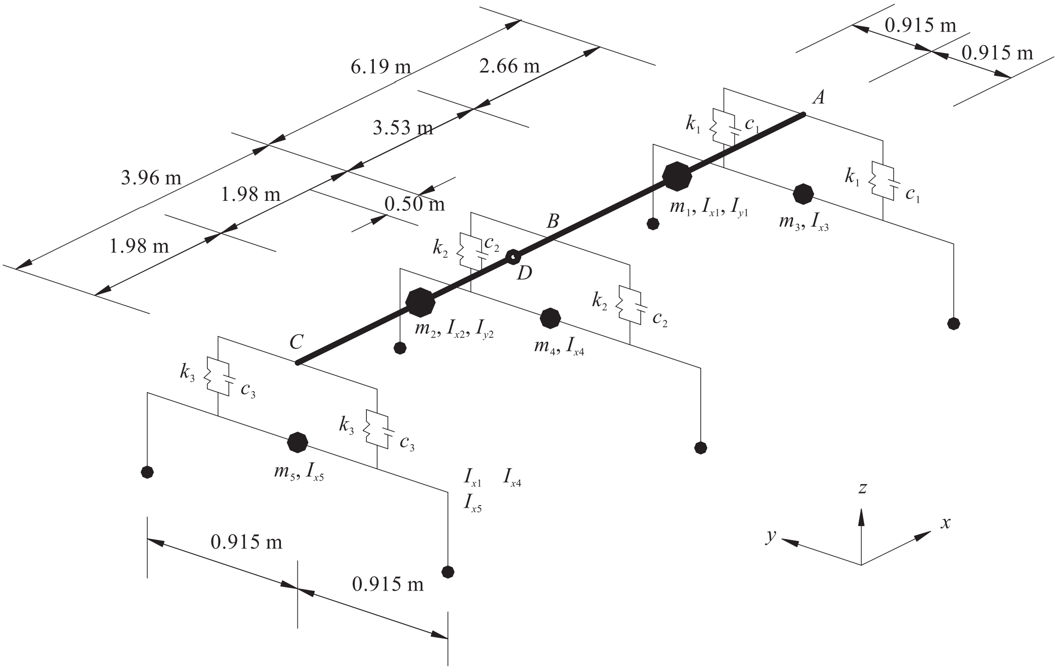


Fig. 3 Vehicle model

There are five independent degrees of freedom (d.o.f.) in the vehicle system, namely, translation d_{z1}, rotation θ_{x1} and rotation θ_{y1} of sprung mass m_1, and translation d_{z2} and rotation θ_{x2} of the sprung mass m_2 with respect to the longitudinal axis x along the direction of motion, the transverse axis y, and the vertical axis z. The rotation about y of mass m_2, θ_{y2}, is related to the above five independent d.o.f.

The unsprung mass m_3, m_4, and m_5 are assumed to be concentrated at the centers of the three axles, respectively. Mass m_3 can undergo vertical translation d_{z3} and a rotation θ_{x3}. Similarly, mass m_4 has vertical translation d_{z4} and a rotation θ_{x4} and mass m_5 has vertical translation d_{z5} and a rotation θ_{x5}. Since mass m_3, m_4 and m_5 are not supported by springs and the wheels are summed to remain in contact with the bridge surface, d_{z3}, θ_{x3}, d_{z4}, θ_{x4}, d_{z5}, and θ_{x5} are not independent but related to the vertical motions of the contact points between the wheels and the bridge surface. Thus, the total number of d.o.f. of the bridge-vehicle system is $N + 5$, in which N is the number of d.o.f. of the bridge structure.

For numerical analysis, the physical properties of the vehicle model are described in Table 1.

Table 1 Physical properties of vehicle

Mass (kg)		Mass moment inertia (kg·m^2)		Axle stiffness (N/m)	
m_1	28 038	I_{x1}	23 448	k_1	1 138 300
m_2	2804	I_{y1}	263 052	k_2	1 138 300
m_3	1752	I_{x2}	4982	k_3	1 138 300
m_4	1402	I_{y2}	26 305		
m_5	1051	I_{x3}	4982		
		I_{x4}	879		
		I_{x5}	879		

3 Free Vibration Analysis

The dynamic characteristics of a box-girder bridge, including its natural frequencies, vibration mode shapes, and mechanical damping properties' are important factors which can significantly affect its stability behavior under traffic loads[3]. Aspect ratio defined as the ratio of the length of a bridge deck to its width is a key parameter than influences the natural frequencies and mode shapes. In this study, the aspect ratio of Bridge A varies from 2 to 4, corresponding to spans of 18.7 m, 28.05 m, and 37.4 m. The aspect ratio of Confederation

Bridge is as high as 36.

Table 2 presents the first eighteen natural vibration frequencies and nature of the vibration modes of Bridge A and Confederation Bridge. As noted, an increase in the aspect ratio of the bridge results in a significant decrease in the frequency. For bridge with short span, the lower modes are lateral flexure or torsion or the combination of the two coupled with longitudinal flexure. The longitudinal flexure is dominant in higher modes but mixed with transverse flexure or torsion. For bridges with long span, the lower modes are pure longitudinal flexure. The governing deformation in higher modes is also longitudinal flexure but occasionally combined with lateral flexure and torsion.

Table 2 Free vibration

Mode No	Bridge A						Confederation Bridge	
	Aspect ratio = 2		Aspect ratio = 3		Aspect ratio = 4			
	Freq. (Hz)	Mode shape	Freq. (Hz)	Mode shape	Freq. (Hz)	Mode shape	Freq. (Hz)	Mode shape
1	5.92	TO-TF	2.97	LF-TF-TO	1.81	LF-TF	0.48	LF
2	9.52	TF	6.74	LF-TF	4.07	LF	0.55	LF
3	9.68	TF	7.99	LF-TF-TO	5.14	LF-TO	0.60	LF
4	10.22	TF	9.82	TF	8.12	LF-TF	1.11	LF
5	10.22	TF	9.84	TF	9.52	LF	1.21	LF
6	11.07	TF	10.20	TF	9.58	LF-TF	1.25	LF
7	11.08	TF	10.21	TF	9.93	LF-TF	1.28	LF
8	12.39	TF	10.31	LF-TF	9.94	LF-TF	1.79	LF
9	12.39	TF	10.38	LF-TF-TO	9.97	LF-TF	2.12	LF-TO
10	12.47	TF	10.43	LF-TF	10.17	LF-TF	2.33	LF-TF
11	12.74	LF-TF	10.72	LF	10.27	LF	2.70	LF-TO
12	12.86	TF	10.72	LF	10.27	LF	3.23	LF-TF
13	13.05	TF-TO	11.45	LF-TF	10.74	LF	3.26	LF-TO
14	13.33	TF	11.45	LF-TF	10.74	LF-TF	3.40	LF-TO
15	13.42	TF-TO	12.33	LF-TF	11.07	LF-TF-TO	3.94	LF-TO
16	13.57	LF-TF	12.40	LF	11.36	TF	4.02	LF-TO
17	14.11	TF	12.40	LF	11.37	LF	4.54	LF-TO
18	14.11	TF	12.65	LF-TF	12.11	LF-TF	4.57	LF-TF

Note: LF – Longitudinal flexure; TF – Transverse flexure; TO – Torsion.

4 Forced Vibration Analysis

For forced vibration analysis the present study focuses on the following aspects that influence the bridge responses:

(1) Number of vehicles on the bridge and their traveling path;
(2) Aspect ratio;
(3) Traveling speed of vehicle;
(4) Damping ratio of vehicle;
(5) Mass ratio defined as the ratio of the total mass of a vehicle to the total mass of a bridge.

All the responses of the bridges subjected to traffic load are based on the equilibrium conditions under dead load. The results are evaluated by peak accelerations and amplification factor (the ratio of the maximum dynamic response for moving vehicle to the maximum static response under equivalent truck loads) of midspan deflection DI.

4.1 Effect of traffic loading pattern

The effect of traffic load patterns has been studied by analyzing the responses of Confederation Bridge and Bridge A with span of 37.4 m. The damping ratio of the bridge was assumed to be 0.02. The bridges contain two traffic lanes. Four load cases shown in Fig. 4 have been considered including: (1) one truck traveling along the centerline of bridge; (2) one truck traveling along the center of lane; (3) two trucks traveling simultaneously side by side along the center of lanes; and (4) four trucks traveling along the center of lanes with two on one lane and the other two on the other lane. The bridge models were then subjected to one to four trucks moving from the left to the right on a smooth road surface at the constant speed of 70 km/h. For Bridge A, only the first three load patterns are considered due to its shorter span length. The results are presented in Table 3.

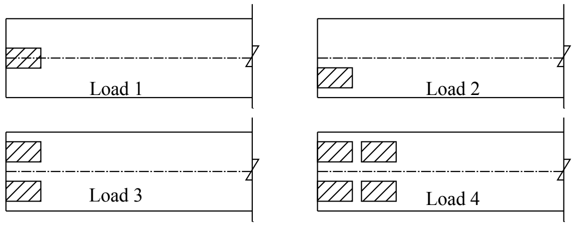


Fig. 4 Traffic load cases

Table 3 Peak mid-span deflections and accelerations of box-girder bridges at vehicle speed = 70 km/h

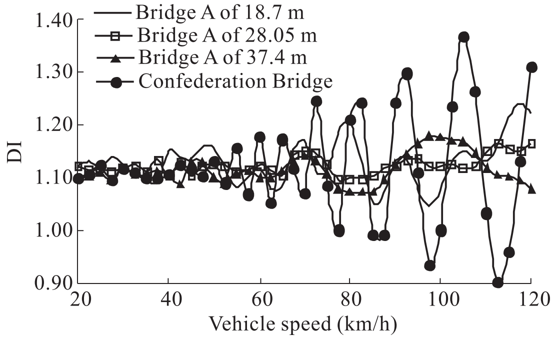
Birdges	Load cases	Static deflection (mm)	Dynamic deflection (mm)	DI	Acceleration (m/s^2)
Confederation Bridge	1	6.84	7.31	1.07	0.76
	2	6.00	6.99	1.17	0.24
	3	11.13	13.02	1.17	0.41
	4	20.97	27.84	1.33	0.39
Bridge A with span of 37.4 m	1	5.85	6.68	1.14	13.40
	2	9.96	10.52	1.06	5.59
	3	9.00	10.06	1.12	5.04
	4	N/A	N/A	N/A	N/A

It can be seen that the peak dynamic response is larger than the peak static response for all the load cases. Eccentric traffic loads produce larger response than central traffic loads. As expected, increasing the number of trucks results in larger peak deflection. It can be observed that one truck moving along the centerline of the bridge produces the largest bridge acceleration for bridge models. Bridge A seems to be more sensitive to eccentric traffic loads than Confederation Bridge, which implies that bridge prototype significantly influences bridge dynamic responses to different load cases.

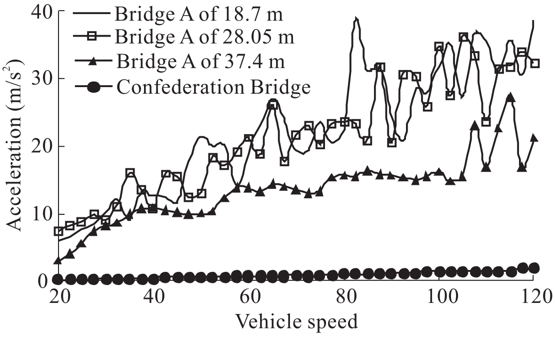
4.2 Effect of traveling speed and aspect ratio

The effect of vehicle speed and aspect ratio were investigated by analyzing the dynamic responses of Confederation Bridge with a span of 442 m corresponding to the aspect ratio of 36 and Bridge A with span of 18.7 m, 28.05 m, and 37.4 m corresponding to the aspect ratio of 2, 3, and 4, respectively. The damping ratio of the bridges is assumed to be 0.02. Load case 1 is adopted, in which one truck moves along the centerline of the bridge. Figure 5 presents the peak amplification factor of deflection DI and peak accelerations as a function of vehicle speed ranging from 20 km/h to 120 km/h.

It can identify that in some cases bridge-vehicle interaction reduces the response, while in others it increases the response, and the changes can be significant. In general, the responses tend to increase with the increase in vehicle speed. The dynamic amplification factors due to bridge-vehicle interaction associated with lower vehicle speed are less pronounced than those corresponding to higher vehicle speed.



(a) Vehicle speed vs. DI



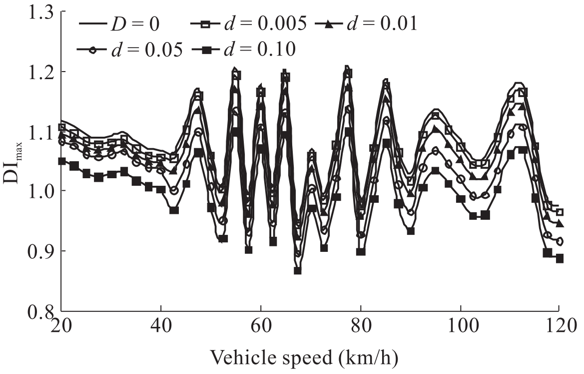
(b) Vehicle speed vs. accelerations

Fig. 5 Amplification factor and peak accelerations varying with vehicle speed

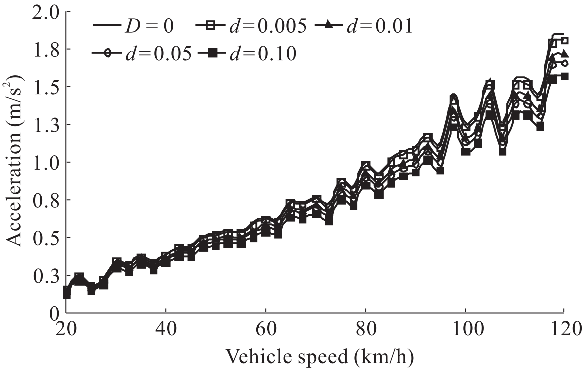
Bridges with different aspect ratios have peak DI occurring at different truck speed. For Bridge A, the maximum DI is obtained at approximately 120 km/h, 80 km/h, and 70 km/h corresponding to aspect ratio 2, 3, and 4, respectively. For Confederation Bridge, the DI reaches as high as 1.38 at about 105 km/h. The peak DI of Confederation Bridge is much larger than that of Bridge A when the truck moves at high speed, which implies that long span bridges are more pronounced to bridge-vehicle interaction than short span bridges. However, bridges with longer-span tend to generate lower acceleration due to the fact that longer bridges usually have flexural dominant modes.

4.3 Effect of vehicle damping ratio

Figure 6 displays amplification factor of deflection and accelerations of Confederation Bridge subjected to load 1 with vehicle damping ratio from 0.0 to 0.1 and vehicle speed ranging from 20 km/h to 120 km/h. It is observed that increasing vehicle damping reduces the response of bridge but the reduction is not significant. Furthermore, introduce of vehicle damping does not change the nature of the bridge response varying with truck speed.



(a) Vehicle speed vs. $\mathrm{DI}_{\max}$

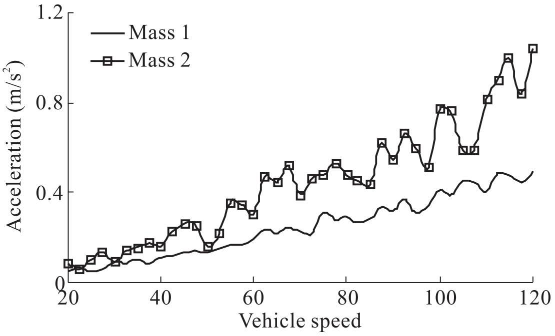


(b) Vehicle speed vs. acceleration

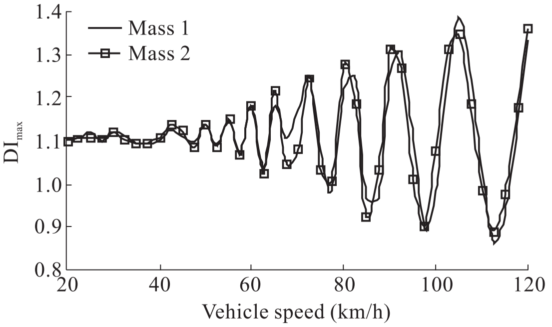
Fig. 6 Effect of vehicle damping ratio on bridge response

4.4 Effect of mass ratio

The effect of mass ratio has been investigated by analyzing the response of Confederation Bridge under load 2. Two cases of truck mass, mass1 and mass 2, have been calculated. Mass 1 uses the exact physical properties shown in Table 1. Mass 2 adopts most of the properties of Mass 1 but doubling the truck weight proportionally. The mass of the bridge deck structure is approximately 17.5×10^{6} kg. Therefore, the mass ratios for mass1 and mass2 to the weight of bridge superstructure are 0.002 and 0.004, respectively. The results are illustrated in Fig. 7 including DI and accelerations as functions of truck speed.



(a) Vehicle speed vs. acceleration



(b) Vehicle speed vs. $\mathrm{DI}_{\max}$

Fig. 7 Effect of mass ratio on bridge response

By comparing the response curves of the two truck weight cases, two important features have been revealed. First, increasing truck weight can result in significant increase of acceleration of the bridge. Second, increasing truck weight might either enlarge or reduce the DI. At higher truck speed, mass 2 tend to produce higher DI than mass 1. Generally speaking, truck mass does affect DI as much as accelerations in the approaches.

5 Conclusions

Based on the above investigations on bridge-vehicle interaction of box-girder bridge, the following conclusions and remarks can be made.

(1) Bridge-vehicle interaction can either increase or reduce bridge responses and the change can be significant. Very long-span bridges are more pronounced to interaction than medium and short-span bridges.

(2) Longer bridges tend to have lower frequencies with flexural dominant mode, which results in lower bridge accelerations.

(3) Increasing vehicle damping reduces the response of bridge but the reduction is not significant.

(4) In general, the dynamic responses of bridge tend to increase with the increase of vehicle speed. The dynamic amplification factors due to bridge-vehicle interaction associated with higher vehicle speed are much more pronounced than lower vehicle speed.

(5) The traffic load patterns play an important role in simulating the dynamic responses of box-girder bridge. Eccentric traffic load tends to produce larger bridge response than central traffic load. Increasing the number of trucks can result in the increase of dynamic response. Distributing the trucks on multiple lanes can reduce the bridge responses.

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