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Improved definition of dynamic load allowance factor for highway bridges

Yongjun Zhou[1a], Zhongguo John Ma[*2], Yu Zhao[1b], Xiongwei Shi[3c] and Shuanhai He[1d]

[1]Department of Highway School, Chang'an University, Middle Section of Nan Erhuan Road, Xi'an, 710064, China
[2]Department of Civil and Environmental Engineering, University of Tennessee Knoxville, 313 John D. Tickle Building, Knoxville, TN 37996-2313, USA
[3]Xi'an Highway Research Institute, South Wenyi Road, Xi'an, 710054, China

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Abstract. The main objective of this paper is to study the dynamic load allowance (DLA) calculation methods for bridges according to the dynamic response curve. A simply-supported concrete bridge with a smooth road surface was taken as an example. A half-vehicle model was employed to calculate the dynamic response of deflection and bending moment in the mid-span section under different vehicle speeds using the vehicle-bridge coupling method. Firstly, DLAs from the conventional methods and code provisions were analyzed and critically evaluated. Then, two improved computing approaches for DLA were proposed. In the first approach, the maximum dynamic response and its corresponding static response or its corresponding minimum response were selected to calculate DLA. The second approach utilized weighted average method to take account of multi-local DLAs. Finally, the DLAs from two approaches were compared with those from other methods. The results show that DLAs obtained from the proposed approaches are greater than those from the conventional methods, which indicate that the current conventional methods underestimate the dynamic response of the structure. The authors recommend that the weighted average method based on experiments be used to compute DLAs because it can reflect the vehicle's whole impact on the bridge.

Keywords: dynamic load allowance (DLA); vehicle-bridge coupling; vehicle oscillation; weighted average method; bridges

1. Introduction

When a vehicle passes a bridge, the loading effect consists of the weight of the vehicle and the dynamic forces due to the oscillation of the vehicle. It is difficult to precisely quantify the dynamic

*Corresponding author, Professor, E-mail: zma2@utk.edu
[a]Professor, E-mail: zyj@chd.edu.cn
[b]Professor, E-mail: zy@gl.chd.edu.cn
[c]Senior Engineer, E-mail: 982199746@qq.com
[d]Professor, E-mail: heshai@chd.edu.cn

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effect produced by a vehicle when passing a bridge. Most bridge design codes typically specify the dynamic loading effect from a vehicle as a fraction of the design live load, which has been referred to as the "dynamic impact factor", "dynamic increment factor", "dynamic load allowance (DLA)", or "dynamic amplification factor". Failure to properly account for dynamic effect can underestimate the stress cycles that contribute to fatigue in bridge components (Mclean and Marsh 1998).

Various definitions have been used for quantifying dynamic load effects, which has led to different conclusions drawn even from the same set of dynamic data (Bakht and Pinjarkar 1989). Mclean and Marsh (1998) mentioned three common definitions for DLA, where all methods use the static response due to a truck "crawling" across a bridge as the reference to define DLA. Beben (2013) presented two methods to determine the static response in term of DLA. In the first method, the static response was directly obtained from static tests. In the second method, the static response was determined based on the filtration of the dynamic response of the structures. Based on the literature review conducted so far, there is little or no discussion or justification for using a particular definition for DLA. However, there exist the following issues regarding DLA.

Firstly, some researchers took only one vehicle into account rather than a number of vehicles when calculating DLA. The maximum dynamic response of the bridge is usually taken as the static design effect multiplied by its corresponding DLA. According to the definition of influence line, the dynamic response of the bridge caused by design vehicles can be written as follows:

$$S_d = \sum (1+\mu_i) P_i y_i \tag{1}$$

Where S_d=the maximum dynamic response of bridge under the moving vehicles; P_i=the weight of the axle, y_i=the corresponding coordinate of influence line at the position of P_i, and μ_i=DLA by the individual P_i. If μ_i is assumed to be the same value, the following equation can be provided

$$S_d = (1+\mu)\sum P_i y_i = (1+\mu) S_t \tag{2}$$

Where S_t=the static design response of the bridge; and μ=the bridge's integrate (or total or equivalent) DLA for the design purpose. Eq. (2) is illustrated in many code provisions.

Comparing Eq. (1) with Eq. (2), it shows that 1+μ should represent the effect of $\Sigma(1+\mu_i)$ of the bridge caused by the design vehicles. In other words, the static response of bridge caused by the design vehicle is amplified by the equivalent μ. And μ should synthetically represent the sum effect of μ_i caused by each axel as much as possible. Usually, this μ is only calculated by the maximum dynamic response point, which is not necessarily the point of interest when checking for fatigue stresses.

Secondly, the current DLA definition is not appropriate because the maximum dynamic increment and the maximum static values do not happen simultaneously (Mclean and Marsh 1998, Kim *et al*. 2009). The maximum dynamic response of the mid-span may not occur when the vehicle is passing the mid-span, where the maximum static response occurs. This can be explained by Fig. 1.

It is easy to locate the maximum dynamic response (i.e., Max. dynamic deflection in Fig. 1). However, it is difficult to investigate the maximum static response (i.e., Max. static deflection in Fig. 1) from the dynamic response curve according to the DLA definition. Sometimes, the maximum static response is obtained by static or crawl test which is based on a series of discrete truck locations. The peak static strain values may be lower than that it would occur for a continuum of static strain data for a truck along the length of the bridge (Hajjar *et al*. 2010). It is

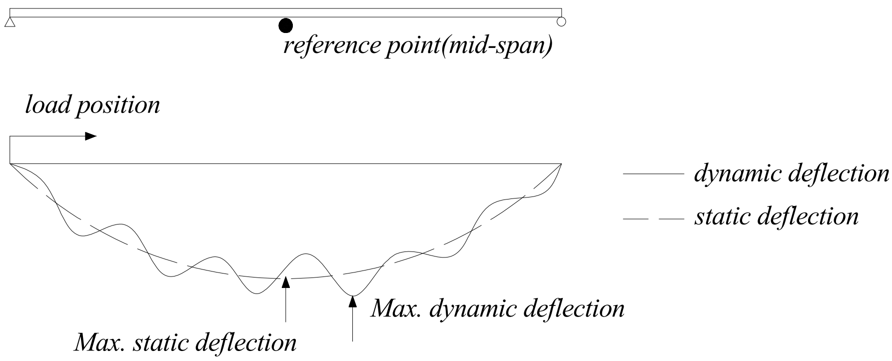


Fig. 1 Deflection of mid-span under a moving vehicle load

also difficult to keep the vehicle in the same lane during the two tests. Additionally, such a requirement for the test is obviously not realistic when data are collected without interrupting the normal traffic.

The objective of the paper is to present one improved approach to calculate DLA. In order to take into account the proper dynamics of the bridge system theoretically, the finite element models of a half vehicle with four degrees-of-freedom (DOF) and a simply-supported concrete beam bridge were built and the vehicle-bridge coupling method was used in the simulation. By comparing the results of three current methods (the conventional definition method, the experiment method and the codes provisions method), two improved approaches are discussed and the approach using weighted average method is finally recommended to take into account the whole procedure of the vehicle excitation.

2. Existing DLA methods

2.1 Conventional DLA definition

The conventional DLA definition is listed as following (Yang *et al*. 1995, Park *et al*. 2005, Kim *et al*. 2009)

$$\mu = \frac{R_d(x)}{R_s(x)} - 1 \tag{3}$$

Where μ=the DLA; $R_d(x)$ and $R_s(x)$ are the maximum dynamic and maximum static responses of the bridge at mid-span section, respectively.

According to this definition, some researchers carried out impact field test which consisted of a crawl and a dynamic test. The crawl speed test was conducted to determine the structure’s response to a static load, and the dynamic test was conducted to determine the structure’s response to a moving load (Clarke *et al*. 1998, Hajjar *et al*. 2010, Jiang *et al*. 2013).

Owing to the limitation to finite element method at that time, in order to calculate the mathematical maximum displacement, Shepherd and Aves (1973) idealized the bridge as a beam and represented the vehicle as a single axle sprung load. They found the DLA implied by the code provisions was inadequate. Bakht and Pinjarkar (1989) presented the technical literature dealing with bridge dynamics in general and dynamic testing of highway bridges in particular. They thought DLA was not a deterministic quantity and some additional factors, such as vehicle type, vehicle weight, vehicle position with respect to reference point and deflection versus strain measurement, may be responsible for misleading conclusions from the test data.

Huang *et al*. (1992) analyzed the DLAs of six continuous multi-girder steel bridges due to vehicles moving across rough bridge decks. The bridges were modeled as grillage beam systems, and the vehicle was simulated as a nonlinear vehicle model with 12 DOFs. A comparison between the DLAs calculated by the presented theory and AASHTO formula was given. The results showed that most DLAs of the six bridges were less than or nearly equal to those calculated by the AASHTO impact equation.

Paultre *et al*. (1992, 1993) and Green (1993) pointed out that the reason why some disagreement exists between provisions of various national bridge codes was that DLA depends, in addition to the maximum span or the natural frequency, on many other parameters that were difficult to take into account with reasonable accuracy. Chang and Lee (1994) theoretically studied vibration behavior of simple-span highway girder bridges with rough surfaces due to heavy trucks. By using the multiple linear regression method they presented empirical formulas for DLAs in terms of span length, vehicle speed, and surface roughness of a bridge deck. Modeling the vehicle as sprung masses and the bridge structure as beam elements, Yang *et al*. (1995) performed a parametric study for various simple and continuous beams bridges exposed to five-axle trucks and developed a new set of DLA formulas which was related to the ratio of the driving frequency to the structure's frequency. Hajjar *et al.* (2010) calculated DLAs for the strain gages of 13 dynamic load tests. The DLAs were calculated by taking the peak dynamic strain for a given test and gage, and dividing by the corresponding peak static strain value, which was determined from the six static tests that used a single truck positioned at different locations along the length of the bridge. Lalthlamuana and Talukdar (2014) conducted a parametric study considering vehicle axle spacing, mass, speed, vehicle flexibility, deck unevenness and eccentricity of vehicle path, then obtained DLA of the bridge response for several combinations of bridge-vehicle parameters. They revealed that flexible modes of vehicle can reduce dynamic response of the bridge to the extent of 30-37% of that caused by rigid vehicle model.

2.2 Experiment method

Since it is difficult to get the static response, it is typically replaced by the equivalent mean response from the dynamic response curve (Bakht *et al*. 1989). DLA by this method is defined as follows

$$\mu = \frac{S_{\max}}{S_{\mathrm{mean}}} - 1 \quad , S_{\mathrm{mean}} = (S_{\max} + S_{\min})/2 \quad \text{or} \quad \mu = \frac{S_{\max} - S_{\min}}{S_{\max} + S_{\min}} \tag{4}$$

where $S_{\max}$, $S_{\min}$, S_{mean} are the maximum, minimum and mean response of the dynamic responses of the bridge at a reference point (usually refer to mid-span section), respectively.

This definition can give fairly reliable results because it was obtained from the calibration test that the maximum static load response is close in magnitude to the corresponding mean response (Bakht and Pinjarkar 1989). In the field test, the DLA can also be calculated as the following equation

$$\mu = \frac{D_{dyn}^{\max} - D_{fil-sta}^{\max}}{D_{fil-sta}^{\max}} \tag{5}$$

where $D_{dyn}^{\max}$ =the maximum dynamic response; and $D_{fil-sta}^{\max}$ the maximum static response that pass through the low range passing filter of 0.6-1.0 Hz (Jung *et al*. 2013).

It is noted that, however, sometimes the static response at a reference point due to the moving vehicle may not be smooth, i.e., it may have "static oscillations". In such cases, finding the mean responses by automatic filtering is made difficult when the period of "static oscillations" matching with the period of dynamic oscillations.

Billing (1984) collected dynamic testing of various configurations of steel, timber, and concrete structures with spans from 5 to 122 m with the objective of obtaining comprehensive data to support OHBDC provisions. Jung *et al*. (2013) utilized the measured DLA data by Eq. (5) from 256 bridges and found that about 32% of those exceeded the Korea design criteria of the DLA. Paeglite and Paeglitis (2013) presented a study of the DLA obtained from the results of the bridges' dynamic load tests carried out from 1990 to 2012 in Latvia. They analyzed the DLAs and compared them to the values of the built-in traffic load models provided in the Eurocode, and found that actual DAL values for even bridge deck surface in most cases were smaller than the values adopted in the Eurcode.

2.3 Design codes (specifications) provisions method

In most cases, the DLA is specified by three different ways: span length of the bridge, natural frequency of the bridge, and a constant value. For example, AASHTO Standard Specifications in USA and KBDS in Korea (Jung *et al*. 2013) expressed DLA as a function of the bridge length. The Chinese Bridge Code (2004) considers DLA as a function of the flexural natural frequency of the bridge. In AASHTO LRFD (2012), DLA is a constant value, where DLA for fatigue/fracture limit state is 0.15 and 0.33 for all other limit states. In Canada, DLA is based on the number of truck axles passing over the bridge (Zhang *et al*. 2003).

3. Proposed DLA methods

3.1 The maximum and its corresponding response method (Approach 1)

For the mid-span section, the vehicle position at the maximum dynamic response does not agree with that leading to the maximum static response. Basically, the conventional definition method uses the definition point when vehicle travels at mid-span which is said to be the maximum dynamic and maximum static response (Yang *et al.* 1995). Based on this point, the first method is presented, which employs the maximum dynamic response and its corresponding static response rather than the maximum static response (i.e., Mode 1). Its principle is specified in the following equation

$$\mu = \frac{A_{dyn}^{\max}}{A_{st}} - 1 \tag{6}$$

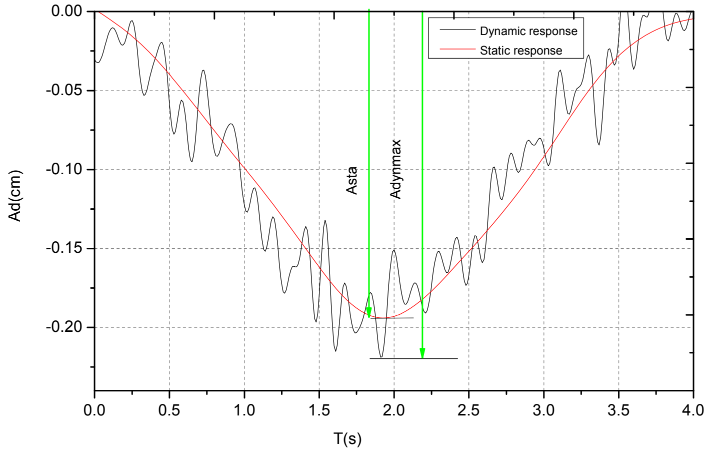


Fig. 2 Principle of approach 1 (Mode 1)

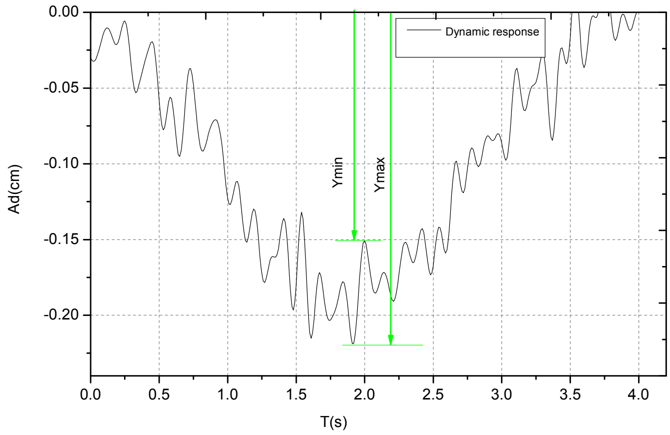


Fig. 3 Principle of Approach 1 (Mode 2)

where $A_{dyn}^{\max}$ and A_{st}=the maximum dynamic response and its corresponding static response of the bridge in the time-history curve under the same vehicle load, respectively. The diagram of the first method is shown in Fig. 2.

If the maximum static response is replaced by the equivalent mean value from the dynamic response curve, this approach, based on experiments method, is called Mode 2 and is put forward as follows

$$\begin{cases} \mu = \dfrac{Y_{\max}}{Y_{mean}} - 1 \\ Y_{mean} = \dfrac{1}{2}\left(Y_{\max} + Y_{\min}\right) \end{cases} \tag{7}$$

where $Y_{\max}$ and $Y_{\min}$= the maximum and its corresponding minimum dynamic response in the dynamic time-history curve, respectively; and Y_{mean}=the mean dynamic response value. The principle of this calculation approach is shown in Fig. 3.

The conventional methods calculate DLA mostly in terms of the mid-span point of the response curve while the first method pays more attention to the maximum dynamic response points. Thus, it can reflect the maximum dynamic response of the bridge related to the corresponding static response at the same vehicle location which represents an improvement over the conventional definition and experiment methods.

3.2 Weighted average method (Approach 2)

Although the above approach can improve DLA, it only considers the dynamic impact of vehicle traveling on certain position while neglecting the impact of the design vehicle on other positions. Researches show that large dynamic responses may be observed in cases where the DLA is quite small (Galdos *et al*. 1993) and vice verse. Meanwhile, in the codes, the integrated dynamic effect of vehicle loads to the bridge is multiplied by a magnification factor (1+μ) on the basis of the static effect. Therefore, DLA should be a whole index which needs to be taken into account of all the impact of the design vehicles on all positions. Thus, it is desirable to have another approach to calculate DLA considering all the local DLAs.

Note that the current methods mainly concern about DLA when vehicle travels near the mid-span, and to avoid jump bounds. This approach suggests that DLA, when vehicle travels near the mid-span, also plays an important role in the integrate DLA. A weighted average method, which is based on the definition method (i.e., Mode 3), is expressed as follows

$$\begin{cases} \mu_{\text{i}} = \dfrac{A_{dyni}}{A_{sti}} - 1 \\ \mu = \sum \mu_i \dfrac{A_{sti}}{\sum_{i=1}^{n} A_{sti}} \end{cases} \tag{8}$$

where A_{dyni}=the ith local maximum dynamic response in the dynamic time-history response; A_{sti}=the ith corresponding static response of the local maximum dynamic response; μ_i=the ith local DLA; n=the number of "wave" in the dynamic time-history response. The principle diagram is illustrated in Fig. 4.

In this approach, the static response of the bridge is obtained by taking the local maximum dynamic responses and their positions of the vehicle, and then placing the static vehicle on the same position in order to get the corresponding static response. If the static response is replaced by the mean value of the dynamic response, this method, based on the experiments method (i.e., Mode 4), can be derived herein. Its DLA computation formula is listed as follows

$$\begin{cases} \mu_i = \dfrac{Y_{\max i}}{Y_{\text{mean}\, i}} - 1 \\ Y_{\text{mean}\, i} = \dfrac{1}{2}(Y_{\max i} + Y_{\min i}) \\ \mu = \sum \mu_i \dfrac{Y_{\text{mean}\, i}}{\sum_{i=1}^{n} Y_{\text{mean}\, i}} \end{cases} \tag{9}$$

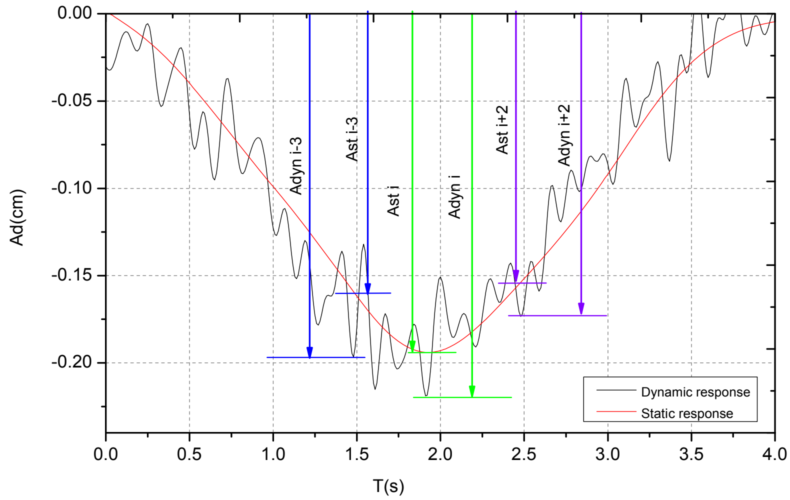


Fig. 4 Principle of Approach 2 (Mode 3)

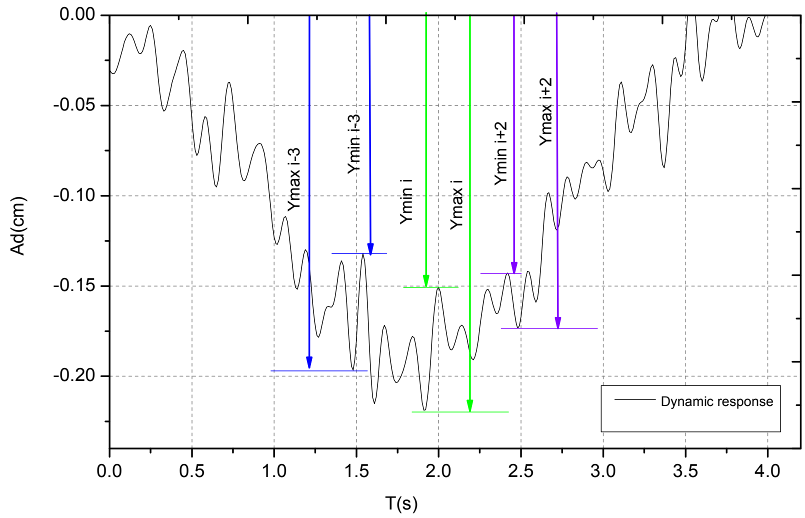


Fig. 5 Principle of Approach 2 (Mode 4)

where $Y_{\max i}$=the ith maximum value from the dynamic response of the time-history curve; $Y_{\min i}$ is the corresponding minimum dynamic response value of $Y_{\max i}$; and $Y_{\text{mean } i}$ is the mean value of dynamic response. The DLA principle is shown in Fig. 5.

4. Numerical simulations and results

4.1 Finite element analysis

When calculating DLA, the vehicle is sometimes idealized as a pair of concentrated forces,

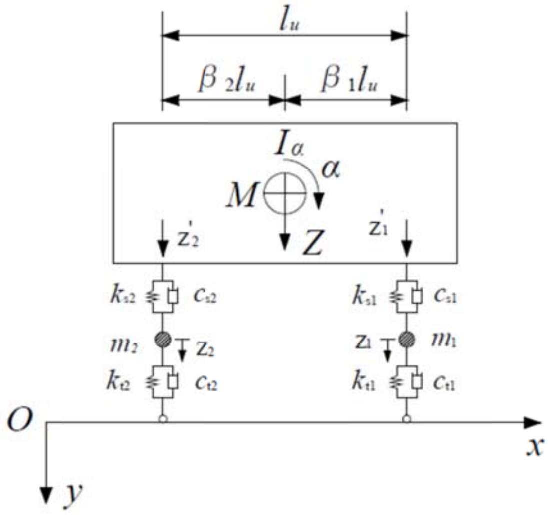


Fig. 6 Schematic of half vehicle with four DOFs

with no mass, however, the suspension system and inertia forces of the vehicle should be incorporated when modeling the vehicle for bridge vibration analysis (Huang *et al.* 1992, Chang and Lee 1994). Thus the vehicle-bridge interaction method is employed in order to get the time history response of the structure.

There are many vehicle models with regard to vehicle-bridge interaction method. The candidate vehicle model should not only represent its vibration properties (mass, damping and stiffness), but also be feasible to simulate. The half vehicle with four DOFs (O'Brien *et al.* 2014, Wang *et al.* 2014) is the major type in bridge design specifications of several countries, so it is adopted in the paper, which is shown in Fig. 6.

In Fig. 6, the vehicle is simplified as a two-spring-damping-mass system. Where M=the mass of the vehicle body; Z=the vertical displacement of the vehicle body; α=the vehicle body's rotational DOF; I_α=the body's rotation moment of inertia; m_i (i=1,2)=the axle mass of suspension and tire; z_i (i=1,2)=the axle's vertical displacement; k_{si} (i=1,2)=the upper spring(suspension) stiffness; c_{si} (i=1,2)=the upper spring damp coefficient; k_{ti} (i=1,2)=the lower spring(tire) stiffness; c_{ti} (i=1,2)=the lower spring damp coefficient; z'_i (i=1,2)=the displacement's of the vehicle body connected to the suspension system; l_u=the distance between the two axles; β_i (i=1,2)=the ratio of axles distance from the mass centre to the distance l_u, and z_b (x_i, t)=the displacement of the bridge's superstructure.

According to the coordinate system shown in Fig. 6, take the spring's natural position of the vehicle as the origin point, the displacement vector of the vehicle is written as

$$z_v = [z_1, z_2, z_1', z_2'] \tag{10}$$

The forces of the vehicle are gravity Mg, $m_i g$, inertia force $M\ddot{Z}$, $I_\alpha \ddot{\alpha}$, $m_i \ddot{z}_i$, upper spring force F_{si} and lower spring force F_{ti}, which can be expressed as

$$\begin{aligned} F_{si} &= k_{si}(z_i' - z_i) + c_{si}(\dot{z}_i' - \dot{z}_i) \\ F_{ti} &= k_{ti}(z_i - z_b(x_i,t)) + c_{ti}(\dot{z}_i - \dot{z}_b(x_i,t)) \end{aligned} \tag{11}$$

The geometrical equation can be written as

$$\begin{aligned} Z &= \beta_1 z_2' + \beta_2 z_1' \\ \alpha &= (z_1' - z_2')/l_u \end{aligned} \tag{12}$$

Based on the general principle of virtual work, the generalized virtual work of the system can be written as

$$\begin{aligned} \delta W_v &= \sum_{i=1}^{2} m_i g \delta z_i + Mg\delta Z - \sum_{i=1}^{2} m_i \ddot{z}_i \delta z_i - M\ddot{Z}\delta Z \\ &- I_\alpha \ddot{\alpha}\, \delta\alpha - \sum_{i=1}^{2} F_{si}\delta(z_i' - z_i) - \sum_{i=1}^{2} F_{ti}\delta(z_i - z_b(x_i, t)) = 0 \end{aligned} \tag{13}$$

Where W_v=the generalized virtual work; $\dot{z}_i$, $\dot{z}_i'$=the velocities of the vehicle; $\dot{z}_b(x_i,t)$=the vibration velocity of the bridge; $\ddot{Z}$, $\ddot{z}_i$=the vertical accelerations of the vehicle; $\ddot{\alpha}$=the angular accelerations of the vehicle.

In order to satisfy Eq. (13), the generalized corresponding coefficient of virtual displacement should be zero. Put Eq. (11) and Eq. (12) into Eq. (13), and the following matrix can be obtained

$$[M_v]\{\ddot{Z}_v\} + [C_v]\{\dot{Z}_v\} + [K_v]\{Z_v\} = \{G_v\} + \{F_{bv}\} \tag{14}$$

$$[M_v] = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & M\beta_2^2 + I_\alpha / l_u^2 & M\beta_1\beta_2 - I_\alpha / l_u^2 \\ 0 & 0 & M\beta_1\beta_2 - I_\alpha / l_u^2 & M\beta_1^2 + I_\alpha / l_u^2 \end{bmatrix}$$

$$[K_v] = \begin{bmatrix} k_{s1} + k_{t1} & 0 & -k_{s1} & 0 \\ 0 & k_{s2} + k_{t2} & 0 & -k_{s2} \\ -k_{s1} & 0 & k_{s1} & 0 \\ 0 & -k_{s2} & 0 & k_{s2} \end{bmatrix}$$

$$[C_v] = \begin{bmatrix} c_{s1} + c_{t1} & 0 & -c_{s1} & 0 \\ 0 & c_{s2} + c_{t2} & 0 & -c_{s2} \\ -c_{s1} & 0 & c_{s1} & 0 \\ 0 & -c_{s2} & 0 & c_{s2} \end{bmatrix}$$

$$\begin{aligned} \{G_v\} &= \{m_1 g,\ m_2 g,\ Mg\beta_2,\ Mg\beta_1\}^T \\ \{F_{bv}\} &= \{k_{t1}Z_{b1} + c_{t1}\dot{Z}_{b1},\ k_{t2}Z_{b2} + c_{t2}\dot{Z}_{b2}, 0, 0\}^T \end{aligned} \tag{15}$$

Where $[M_v]$, $[C_v]$, $[K_v]$=the mass, damping and stiffness matrices of the vehicle, respectively; $\{F_{bv}\}$=the vector of the vehicle-bridge interaction (contact) forces acting on the vehicle; $\{G_v\}$= gravity force vector; and $[Z_v]$, $[\dot{Z}_v]$, $[\ddot{Z}_v]$=the displacement, velocity and acceleration vectors of the vehicle, respectively.

When studying the vibration of vehicle-bridge coupling system, the bridge is usually simulated as spatial beam element and two hypothesis are made: (1) ignore the influence of bearing system and pile-soil-structure interaction and (2) ignore the deformation of beam's section.

Since bridge is simulated as multi-degree-of-freedom system, its vibration equation can be written as follows

$$[M_b]\{\ddot{Z}_b\}+[C_b]\{\dot{Z}_b\}+[K_b]\{Z_b\}=\{F_b\} \tag{16}$$

Where $[M_b]$, $[C_b]$, $[K_b]$=the mass, damping, and stiffness matrices of the bridge, respectively; $\{Z_b\}$, $\{\dot{Z}_b\}$, $\{\ddot{Z}_b\}$=the displacement, velocity and acceleration vectors of the bridge, respectively; and $\{F_b\}$=vector of the vehicle–bridge interaction(contact) forces acting on the bridge.

Deterioration can occur at both the bridge deck and joints due to several factors such as aging, environmental conditions, corrosion, etc. Although bridge deck surface condition is a very important factor that affects the dynamic responses of both the bridge and vehicle, the effect of deck surface condition on the DLA is not discussed in this paper, and the bridge deck is assumed to be smooth for the case that the authors only illustrate how to get the realistic dynamic response of the bridge.

Using the displacement relationship and the interaction force relationship at the contact points between the vehicle and bridge, the vibration equations of the bridge and vehicle were then combined, thus the vehicle-bridge coupling system can be established. Then, the vibration data system was processed by using the fourth-order RungeKutta method in the time domain, which can be referred to Deng and Cai (2010) for more details.

4.3 Bridge and vehicle details

A simply-supported bridge is dynamically characterized so as to illustrate the principle of new approach of computing DLA. The parameters of the bridge are as follows:

The span L is 40 m, the stiffness of the bridge EI is 1.28×10^{11} N·m^2, the constant mass per unit length of the bridge is 1.20×10^4 kg/m, and the deck surface is assumed to be smooth.

The parameters of the vehicle are listed as follows:

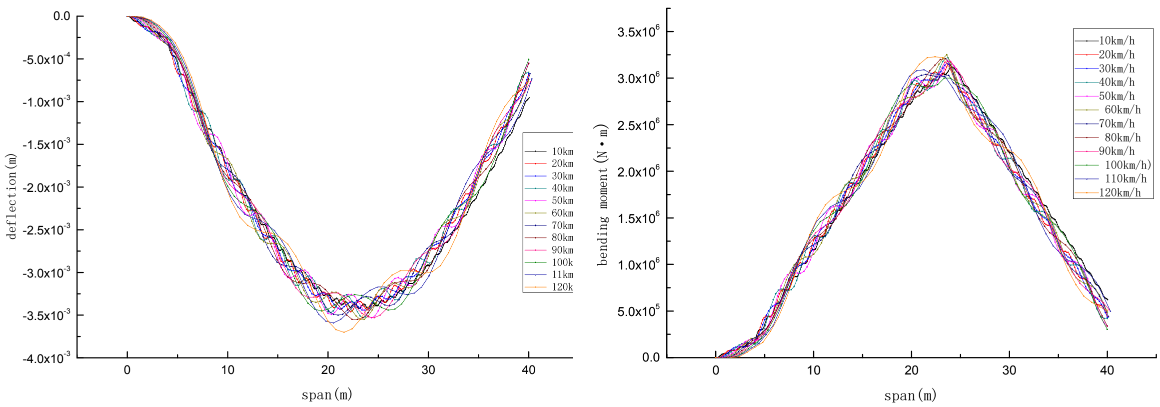
m_1=m_2=4330 kg, M=24790 kg, I_u=3.625 m, $\beta_1 l_u$=1.787 m, $\beta_2 l_u$=1.838 m, K_{ti}=4.28×10^6 N/m, C_{ti}=9.8×10^5 N·S/m, K_{si}=2.54×10^6 N/m, C_{si}=1.96×10^6 N·S/m, I_α=3.258×10^6 kg·m^2

4.4 Results and discussions

Twelve load cases were designed according to the speed of vehicle from 10 km/h to 120 km/h with intervals of 10 km/h. Mid-span section was taken as a reference point, then its dynamic time-history curve of deflection and bending moment was obtained. In order to illustrate the relationship of maximum dynamic response with vehicle position, the time history of x axle is listed verse the position of vehicle instead of time sequence, which is detailed in Fig. 7. In Fig. 7, x axle stands for the distance of back axle of vehicle from the end of abutment, y axle stands for the moment or deflection of the mid-span.

Then, using the conventional definition method, experiment method and code provision method individually, the DLA results are calculated and listed in Table 1.

For the case of bridge type and vehicle varieties, it would be difficult to describe DLA with respect to the vehicle speed. Therefore, vehicle speed is not treated as a variable in the proposed DLA expressions and is averagely expressed by the following equation.



(a) Deflection (b) Bending moment

Fig. 7 Time-history curve of the mid-span section with respect to vehicle position

Table 1 DLA results by conventional methods

Method	v_i (km/h)	10	20	30	40	50	60	70	80	90	100	110	120	Average
Definition method	Deflection	0.008	0.017	0.023	0.032	0.039	0.059	0.029	0.061	0.055	0.024	0.072	0.064	0.040
	Bending moment	0.001	0.028	0.059	0.080	0.005	0.087	0.019	0.075	0.064	0.007	0.033	0.019	0.040
Experiment method	Deflection	0.011	0.027	0.012	0.029	0.033	0.047	0.024	0.065	0.044	0.026	0.062	0.09	0.039
	Bending moment	0.013	0.029	0.030	0.057	0.018	0.075	0.004	0.098	0.062	0.018	0.032	0.081	0.043
Chinese Code (2004)		0.190												
AASHTO LRFD (2012)		0.33												

$$\mu = \frac{\sum_{j=1}^{12} \mu_j}{12} \tag{17}$$

Where μ=the integrate DLA for the bridge; and μ_j=the jth load case (vehicle speed) of the bridge using the mentioned methods or approaches.

From the dynamic response curve, it can be observed that the maximum dynamic response does not necessarily occur when the vehicle travel at the mid-span section. On the contrast, it maybe "delay" from the mid-span section, which can be supported by the findings of Kim *et al*. (2009). Based on this point, it is necessary to reevaluate DLA computing method.

4.4.1 Results based on conventional methods

As is depicted in Table 1, if the definition method and experiment method use mid-span point (the maximum static response point) in the time-history curve to calculate DLA, the deflection DLA by definition method are relatively close to the deflection DLA by experiment method with a difference of 10%, so does the bending moment. But the deflection DLA from both methods are

Table 2 DLA results by Approach 1

Method	v_i (km/h)	10	20	30	40	50	60	70	80	90	100	110	120	Average
Mode 1	Deflection	0.099	0.081	0.126	0.148	0.190	0.143	0.063	0.135	0.206	0.023	0.080	0.138	0.119
	Bending moment	0.118	0.117	0.118	0.145	0.130	0.148	0.032	0.132	0.136	0.075	0.045	0.112	0.109
Mode 2	Deflection	0.008	0.021	0.025	0.051	0.070	0.063	0.089	0.068	0.049	0.032	0.062	0.108	0.054
	Bending moment	0.012	0.024	0.045	0.088	0.128	0.088	0.033	0.113	0.073	0.036	0.032	0.127	0.067
Chinese Code (2004)		0.190												
AASHTO LRFD (2012)		0.33												

30% less than those of bending moment, and the deflection DLA and bending moment DLA are smaller than those in Chinese Bridge Code (2004) and AASHTO LRFD (2012).

4.4.2 Results based on proposed Approach 1

As discussed earlier, Approach 1 takes the advantage of the maximum point of dynamic response, its results are listed in the Table 2. The comparison of DLA results by the different methods and approaches are presented in Fig. 8. From the Table 2 and Fig. 8, the following outcomes are obtained:

(1) Although it is known that vehicle speed influences DLA, the relationship between vehicle speed and DLA is not obvious in this study even if it is a simply-supported beam bridge. So the DLA calculation is suggested to ignore the impact of vehicle speed, as specified in all codes.

(2) The DLAs calculated from the maximum dynamic effect point of the time-history curves (i.e., Approach 1) are greater than those using the conventional definition method and experiment method. Wherein, the deflection DLA by mode 1 is three times larger than that of the conventional definition method, and the bending moment DLA by mode 1 is more than twice of that by the definition method. The difference between the mode 2 and conventional experiment method is also obvious. The deflection DLA by mode 2 is 38% more than that of conventional experiment method and its bending moment DLA is 56% greater when compared with that of conventional experiment method. At the same time, DLA from two modes are smaller than the ones by the mentioned two code provisions.

4.4.3 Results based on proposed Approach 2

Approach 2 uses the weighed average principle based on the definition method and experiment method, and the DLA results are listed in the Table 3. The comparison of DLA results by the different methods and approaches is presented in Fig. 8. The following conclusions can be observed:

(1) As to the weighed average principle, DLAs are also greater than the ones by the conventional definition and experiment method. Wherein, the deflection DAL and the bending moment DAL by Mode 3 are five times and two times greater compared to the definition method, respectively. Bending moment DLA from mode 4 increases 20% compared to the experiment method DLA but the deflection DLA is almost the same with experiment method DLA. By comparison, the moment DLA from mode 3 is 17% less than that of mode 1, but the deflection DAL from mode 3 is 88% greater than that of mode 1. And all the DLA results by mode 4 are

Table 3 DLA results by Approach 2

Method \ v_i (km/h)		10	20	30	40	50	60	70	80	90	100	110	120	Average
Mode 3	Deflection	0.206	0.256	0.160	0.315	0.294	0.236	0.157	0.135	0.206	0.227	0.213	0.282	0.224
	Bending moment	0.072	0.08	0.067	0.105	0.059	0.148	0.055	0.132	0.136	0.075	0.045	0.112	0.091
Mode 4	Deflection	0.011	0.029	0.022	0.078	0.065	0.034	0.027	0.035	0.03	0.029	0.039	0.061	0.038
	Bending moment	0.027	0.041	0.017	0.074	0.071	0.045	0.008	0.113	0.068	0.016	0.032	0.119	0.053
Chinese code 2004		0.190												
AASHTO LRFD 2012		0.33												

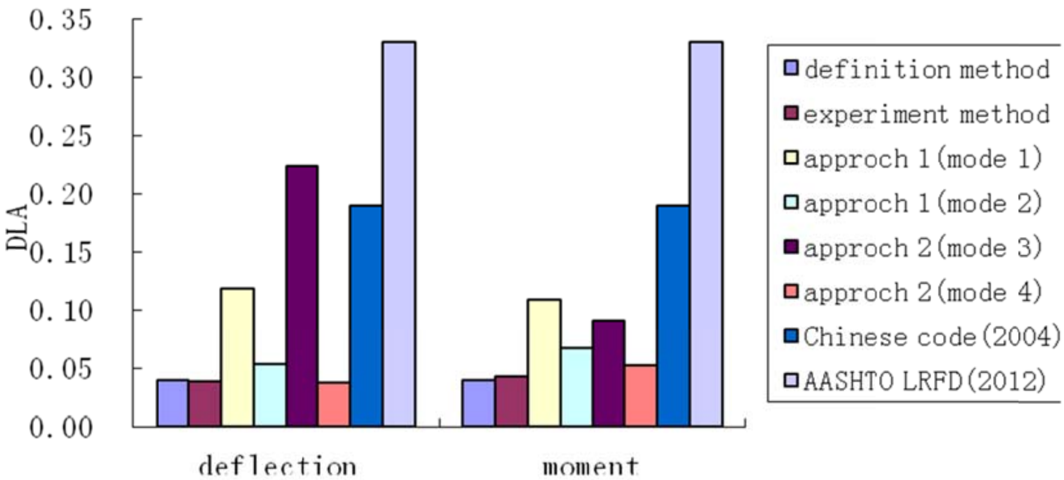


Fig. 8 Comparison of DLA by different methods and approaches

20-30% less than those of mode 2.

(2) The maximum deflection response may not be consistent with bending moment response, so their DLAs are of a little difference. From the two conventional methods, it seems that the deflection DLA equal to that of bending moment DLA. But for the mode 1, the deflection DLA is about 10% greater than the bending moment DLA. For the mode 2, the former is about 20% less than the latter. For the mode 3, the former is more than twice of the latter; and for the mode 4, the former is 30% less than the latter. Therefore their DLA formulas are suggested to be specified separately if it is necessary. Besides, as DLA is mainly proportioned to satisfy the requirement at strength limit state, rather than the service limit state, the deflection DLA is usually ignored. From this viewpoint, it is suggested to use bending moment DLA rather than strain DLA. In the field test, strain gages instead of defection gages should be amounted to get the dynamic time history response of the structure.

(3) As for the two different calculation methods, DLA from definition methods, Mode 1 and Mode 3, varied from 0.040 to 0.224. Whereas, using the experiment methods, Mode 2 and Mode 4, DLA varied from 0.039 to 0.067. So it seems that the experiment method is more stable than the

definition method. Mode 2 is more stable than Mode 1 while Mode 4 is more stable than Mode 3. What's more, DLA using two presented approaches are greater than those calculated by the conventional methods, which shows that the current DLA computing methods may underestimate the dynamic response of the structure. Though most of DLAs are smaller than the mentioned two codes, when it is referred to Mode 3, the deflection DLA is greater than that of Chinese Bridge Code (2004). AASHTO LRFD (2012) prediction seems to be more conservative. However, it is not clear if the requirement of safety could be satisfied under the rough deck condition, it is preferred to use weighed average principle to calculate DLA because it can reflect the whole impact of vehicle on the bridge.

(4) Finally, it is difficult to get the static value from the dynamic response of the bridge in the field test unless the vehicle acts on the corresponding positions. To simplify the design, the equivalent static effect is essential, which means mode 4 is recommended to calculate DLA.

5. Conclusions

For developing a meaningful method to compute DLA, a half vehicle model with four DOFs is adopted in bridge-vehicle interaction system to obtain the realistic dynamic response of a simply-supported bridge. Two approaches to computing DLA are presented. Finally, the weighted average principle is recommended. The following conclusions can be drawn from the study:

(1) The relationship between the vehicle speed and DLA is not obvious in this study even if it is a simply-supported beam bridge. So the formula of DLA is suggested to ignore the impact of vehicle speed.

(2) The DLA obtained from the proposed approaches are greater than those obtianed by the conventional definition and experimental methods, which shows that the current conventional DLA computing methods may underestimate the dynamic response of the structure.

(3) All the results in this study demonstrated that the deflection DLAs are different from bending moment ones. Since DLA is, in the most cases, utilized to satisfy the requirement at strength limit state, it is suggested to measure bending moment DLA instead of deflection DLA when evaluating the bridge.

(4) Most DLAs results in this study are smaller than the calculation results by the Chinese Design Code (2004), and all the DLAs results in this study are less than those obtained by AASHTO LRFD (2012) and DHBDC (1991) Code, which indicates that these codes are conservative on the calculation of DLA under the condition of smooth deck.

(5) It is recommended to use the weighted average principle based on experiment method to calculate DLA, since it can reflect the vehicle's whole impact on the bridge.

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