Effect of vehicle speed and road surface roughness on the impact factor of simply supported bridges due to IRC Class A and B loading

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Abstract

Indian Road Congress (IRC)-06 specifies consideration of impact factor for dynamic analysis of bridge loaded with Class A and Class B vehicles. As per IRC-06 specifications, the impact factor is estimated based only on the span length of the bridge. In the present study, the effect of vehicle speed, road surface roughness condition and span length of the bridge on the impact factor is investigated. The dynamic response of a simply supported bridge loaded with IRC Class A and Class B vehicle loads are considered for the study. For simplifications, the vehicles are idealized as a series of moving mass spring damper system. The interaction between the bridge and vehicle is accomplished by coupling the equation of motion using the interaction force at the contact point of the wheel and bridge. The coupled equation of motion is solved using Newmark's beta method. The model is validated using past available literature. The vehicle is considered to move at a consistent speed between 20 and 100 km/h. The excitation caused due to the presence of road surface roughness at various vehicle speeds on the bridge response with span lengths varying between 20 and 100 m is investigated. Parametric studies are also conducted using frequency ratio. From the studies, it is observed that the response of the bridge subjected to IRC Class A vehicle is 40% higher than the response of the bridge subjected to IRC Class B vehicle. It is also observed from the parametric study that, the bridge response becomes critical when the vehicle moves at resonance speed and the amplitude increases with deterioration of road surface condition. The results of the impact factor study show that IRC-06 specifications underestimate the response of the bridge for high speed moving vehicles under different road surface conditions. The findings of this study can be utilized to update the IRC specifications at the time of analysis and design of both short and as well as long-span highway bridges.

Keywords IRC loading · Vehicle speed · Road surface condition · Impact factor · Vehicle bridge interaction · Frequency parameter

1 Introduction

With expanding open interest, the business activity of fast vehicles become increasingly famous. As a result of the gigantic measure of dynamic vitality conveyed by the fast vehicles, it might collaborate essentially with the extension structure and even reverberate with it in specific situations. This roused the analysts to attempt different new methods for researching the response of the vehicle

bridge interaction system. The majority of the research in this area is limited to wind and earthquake loading but ignoring the effect of high-speed vehicle bridge interaction [1]. The bridge response to a moving vehicle is governed by many parameters such as bridge span, vehicle speed, the natural frequency of the bridge, road surface roughness, etc. The significant effect of these parameters is difficult to estimate due to the complex behavior of both bridge and vehicle [2]. Some of these parameters have

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been identified by the researchers recently [3, 4] which has a significant effect on the amplification of dynamic responses with respect to static response. Other researchers [5–11] have also investigated the complexity of vehicle bridge interaction but a single quantitative expression as a function of all these parameters has not been developed yet. In the past studies [12, 13], the influence of road surface irregularities has been considered and the bridge response is obtained for a truckload. Huang et al. [13] established a method for vehicle bridge interaction considering the road surface irregularities and vehicle speed. A 3D bridge-vehicle coupling model has been established by Deng and Cai [14] for simulation of bridge response to a moving vehicle. The effect of dead load and impact factor to produce the absolute maximum moment was studied by estimating the number of wheels and location of IRC Class A and Class 70 R wheeled vehicles [15]. The impact factor of various types of bridges due to moving loads have been estimated using the vehicle bridge interaction analysis [16–21]. Banerjee et al. [22] studied the effect of corrosion on the strength and stiffness of a slab girder bridge and concluded that the moment carrying capacity of the girder reduces to lesser than the actual capacity under dead load and rated live load. Nguyen et al. [23] used the finite element method and Monte Carlo simulation for random vibration analysis of vehicle bridge interaction considering the road surface roughness profile. The authors suggested that the impact factor increases with the deterioration of road surface roughness conditions.

The vehicle can be modeled as a moving force as shown in Fig. 1a. This model is progressively powerful when the proportion of the vehicle mass to the bridge mass is little and where the response of the bridge is the primary concern. Moving mass model (Fig. 1b) is another approach used to model the moving vehicles where the vehicle load is idealized as a mass accounting for the inertia effect of the vehicle. Another model that is utilized to consider the bouncing impact of the vehicle is the moving spring-mass model (Fig. 1c). Such an impact is relied upon to be marked in the nearness of asphalt surface abnormalities. In this methodology, the vehicle is demonstrated as a mass with a spring and a damper. The structural analysis mainly consists

of both static and dynamic analysis [24, 25]. Dynamic forces that excite the bridge structures are vehicle motion, earthquake, streamflow and winds [12, 26]. At the point when a bar exposed to a moving load, the moving load changes in position along the span of the bridge, hence handling of this type of load needs to be considered carefully accounting for the dynamic effect of the vehicle [27]. In light of the Euler–Bernoulli beam theory, analytical methods have been proposed to take care of basic moving load problems [12, 28]. Using modal superposition method Wang [29] analyzed multi-span Timoshenko beams for concentrated moving load and compared with Euler–Bernoulli beam responses. Using the modal analysis Wang and Lin [30] further studied multi-span Timoshenko frames excited by a moving force. Considering the inertia of the vehicle Wu et al. [31] have consolidated the finite element and analytical methods to analyze the bridge structures subjected to moving bodies. The characteristic response spectrum and dynamic amplification factor for damped beams are estimated by Savin [32]. Including the damping effect, Michaltsos [33] has evaluated the dynamic conduct of a solitary span beam for moving loads at different speeds. Oniszcuk [34] has analyzed the case of undamped forced transverse vibration for the double-beam system. Further using the Classical modal expansion method, the problem is formulated and solved for a simply supported beam. Composite beams subjected to moving random force considering acceleration, deacceleration and constant speed are analyzed by Zibdeh and Hilal [35]. Various parameters have been considered to compute the dynamic impact factor including the position of vehicle load, vehicle weight, traveling speed, road surface conditions, road roughness correlation, number of loading lanes, etc. [12, 36–38]. The standard vehicle loads in the designing of the bridge are different in different countries based on their code of practice. HS20-44 Truck, H15-44, H20-44, and HS15-44 are some common types of vehicles that have been considered by the analysts to investigate the bridge-vehicle interaction response [14]. However, the effect of vehicle speed and road surface roughness condition (RSC) on the dynamic response of the bridges subjected to IRC Class A and Class B loading has not been studied yet which is also neglected in IRC-06.

Fig. 1 **a** Moving force model, **b** moving mass model, **c** Spring mass damper model

2 Research significance

This study focuses on understanding and evaluating the dynamic responses of bridge structure subjected to moving IRC Class A and Class B loading. As specified in the Indian Road Congress (IRC-6,2014) [39], the impact on the bridge structure due to the moving vehicle depends on the type of bridges namely Steel Bridge and Reinforced Cement Concrete (RCC) Bridge and span length. The impact factor due to the moving IRC Class A and B loading is calculated as below (IRC-06, 2014):

$$I = \frac{A}{B + L} \quad (1)$$

where A and B are constants and are dependent on the type of reinforced concrete bridge and steel bridge. L is the span of the bridge. It appears from the Eq. (1) that, the impact is the same for a particular type of bridge irrespective of the speed of the vehicles and irregularities present on the bridge deck surface. However, past studies [40, 41] have shown that the speed of the vehicle and road surface roughness significantly affects the response of the bridge. In this article, the authors have addressed this problem and investigated the effect of IRC Class-A and Class-B

vehicle speed and road surface roughness condition (RSC) on the response of the simply supported bridges. The two-vehicle loadings are shown in Fig. 2a, b. The loads are in ton and distances between successive loads and vehicles are in meter as per IRC-6 specifications.

3 Impact factor

The impact caused in the Highway bridge structures resulting from the moving of vehicles over it is an important subject mostly concerned with the bridge engineers. When a vehicle moves over the bridge it imposes static and dynamic loads. Static loads are generated from the weight of the vehicle and the dynamic loads are generated due to the interaction of moving vehicles with bridge surfaces. Usually in the design of new bridges or at the time of evaluation of existing bridges a factor is considered to take into account the effect of dynamic vehicle load which is known as the Impact factor, where the static load is magnified by some factor to cover the dynamic effect of vehicle load. In IRC-06 (2014) specification, the impact factor is defined differently. However, the impact factor generally

Fig. 2 **a** IRC Class-A vehicle loading, **b** IRC Class-B vehicle loading

is a function of maximum static response and maximum dynamic response as follows:

$$\text{Impact factor (IF)} = \frac{u_{\text{dyn}} - \Delta_{\text{st}}}{\Delta_{\text{st}}} \quad (2)$$

where u_{dyn} and Δ_{st} are the maximum dynamic and static deflection at a certain location of the respectively.

4 Vehicle bridge coupled system

IRC class A and class B vehicle contains multiple axle loads as shown in Fig. 2. The moving load model can be used in vehicle bridge interaction analysis to estimate the bridge response due to moving vehicles. However, the moving load model cannot take into account the bouncing effect of the vehicle in the presence of road surface irregularities. To overcome this issue IRC Class A and B vehicles are idealized as a series of moving spring mass damper systems. The equation of motion of the vehicle can be written as:

$$[M_v] \{\ddot{q}_v\} + [C_v] \{\dot{q}_v\} + [K_v] \{q_v\} = \{P_v\} \quad (3)$$

where $[M_v]$, $[C_v]$, $[K_v]$ are the mass, damping and stiffness matrix of the moving spring mass damper system; $\{q_v\}$ is the displacement vector of the vehicle; $\{p_v\}$ is the vector of vehicle bridge interaction force acting on the vehicle (Fig. 3).

The mass, stiffness and damping matrix for n number of moving spring mass damper system can be written as follows:

$$[M_v] = \begin{bmatrix} M_{v1} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & M_{vn} \end{bmatrix}, \quad [K_v] = \begin{bmatrix} K_{v1} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & K_{vn} \end{bmatrix}$$

$$[C_v] = \begin{bmatrix} C_{v1} & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & C_{vn} \end{bmatrix}, \quad \{P_v\} = \begin{bmatrix} K_{v1}q_{v1} + C_{v1}\dot{q}_{v1} \\ \vdots \\ K_{vn}q_{vn} + C_{vn}\dot{q}_{vn} \end{bmatrix} \quad (4)$$

$$\{q_v\} = \begin{bmatrix} q_{v1} \\ \vdots \\ q_{vn} \end{bmatrix}$$

The bridge equation of motion can be written as:

$$[M_b] \{\ddot{q}_b\} + [C_b] \{\dot{q}_b\} + [K_b] \{q_b\} = \{P_b\} \quad (5)$$

where $[M_b]$, $[C_b]$, $[K_b]$ are the mass, damping and stiffness matrix of the bridge, $\{q_b\}$ is the displacement vector of the bridge, $\{p_b\}$ is the vehicle bridge interaction force vector acting on the bridge.

4.1 Road surface roughness profile

When a new bridge is constructed, its deck surface remains smooth initially but with time due to traffic movement, the deck starts deteriorating. There could be other reasons also for surface deterioration like corrosion, environmental factors, temperature variations, etc. When a vehicle moves over a deteriorated surface additional dynamic load is generated due to the interaction of moving vehicles with bridge surface. In this study, the effect of this dynamic load due to the deteriorated surface is studied. The deck surfaces roughness profile is generated by the inverse Fourier transformation of a power spectral density function (PSD). The surface profile generated here is assumed to be of zero-mean Gaussian random process. The PSD function is shown below:

$$r(x) = \sum_1^N \sqrt{2G(n_k) \Delta n \cos(2\pi n_k x + \theta_k)} \quad (6)$$

$$G_d(n) = G_d(n_0) \left(\frac{n}{n_0} \right)^{-w} \quad (n_1 < n < n_2) \quad (7)$$

where x is the horizontal distance of the deck surface profile varies from 0 to L , L is the length of the bridge deck profile, n_1 and n_2 are the upper and lower cut off frequencies, $\Delta n = (n_2 - n_1)/N$ and $N = L/B$; B is the sampling frequency of the deck surface profile; θ_k is the random phase angle between 0 and 2π . Based on the ISO-8608(2016) [42] specifications, five different categories of road surface roughness profile is generated which are classified as "Very good", "Good", "Average", "Poor" and "Very poor". The roughness coefficient $G_d(n_0)$ is

Fig. 3 Moving spring-mass model moving on the bridge

used for the classification and is selected based on ISO 8608 specifications. The value of $G_d(n_0)$ is considered as $32 \times 10^{-6} \text{ m}^3/\text{cycle}$, $128 \times 10^{-6} \text{ m}^3/\text{cycle}$, $512 \times 10^{-6} \text{ m}^3/\text{cycle}$, $2048 \times 10^{-6} \text{ m}^3/\text{cycle}$, $8192 \times 10^{-6} \text{ m}^3/\text{cycle}$ for “Very good”, “Good”, “Average”, “Poor” and “Very poor” road surface condition (RSC) respectively. In the present study, the random phase angle is kept the same for different road surface conditions with varying roughness coefficient. The same signal is only multiplied by a constant to compare the bridge response obtained under different road surface conditions and also to obtain the maximum response of the bridge. The values for upper and lower cutoff frequency is taken as 0.011 m^{-1} and 2.83 m^{-1} . The value of N is taken as 1000. Figure 4 shows the five different categories of the road surface roughness generated to simulate the deck surface profile of the bridge.

4.2 Complete model construction

The equation of motion of the vehicle bridge interaction can be combined using the interaction force relationship of bridge and vehicle. Thus, the combined equation of motion of the vehicle and bridge can be written as [43]:

$$\begin{bmatrix} M_{nv} \\ M_b \end{bmatrix} \begin{Bmatrix} \ddot{q}_{nv}(t) \\ \ddot{q}_b(t) \end{Bmatrix} + \begin{bmatrix} C_{nv} & -C_{nv}\varphi(x)^T \\ -C_{nv}\varphi(x) & C_b + C_{nv}\varphi(x)\varphi(x)^T \end{bmatrix} \begin{Bmatrix} \dot{q}_{nv}(t) \\ \dot{q}_b(t) \end{Bmatrix} + \begin{bmatrix} K_{nv} & -K_{nv}\varphi(x)^T - C_{nv}V\varphi'(x)^T \\ -K_{nv}\varphi(x) & K_b + C_{nv}V\varphi(x)\varphi'(x)^T + K_v\varphi(x)\varphi(x)^T \end{bmatrix} \begin{Bmatrix} q_{nv}(t) \\ q_b(t) \end{Bmatrix} = \begin{Bmatrix} C_{nv}Vr'(x) + K_{nv}r(x) \\ -C_{nv}r'(x)\varphi(x) - K_{nv}r(x)\varphi(x) - M_{nv}g\varphi(x) \end{Bmatrix} \quad (8)$$

Here M_{nv} , C_{nv} , K_{nv} is the mass, damping and stiffness matrix of the vehicle; $\varphi(x)$ is the mode shape of the bridge; V is the vehicle speed; $r(x)$ is the roughness value at position x on the bridge and $r'(x)$ is the first derivative of $r(x)$; n is the number of vehicle axles present on the bridge. The right-hand side of the equation represents the vehicle bridge interaction forces and it is clear that the presence of road surface roughness affects the contact forces only. The above-coupled equation is solved using Newmark's beta method. The time step for the solution is taken as 0.0001. The IRC Class A and B loading have eight axles and each axle is idealized as moving spring mass damper system. To get the desired accuracy for the bridge response first 30 modes of the bridge are considered. A MATLAB program is developed to solve the coupled equation of motion and the results are obtained in terms of displacement velocity and acceleration of the bridge.

The parametric study is conducted using a non-dimensional frequency parameter S_n which can be defined as the ratio of bridge frequency to the vehicle's driving frequency. The vehicle's driving frequency

(ω) can be expressed as $\omega = \pi V/L$. Thus, the frequency parameter can be given as follows [44]:

$$S_n = \frac{\omega}{\omega_{bn}} = \frac{\pi V}{L\omega_{bn}} \quad (9)$$

where L is the length of the bridge, V is the vehicle's traveling speed, ω_{bn} is the bridge frequency of n th mode. As it can be seen that the frequency parameter is the function of bridge properties and vehicle speed. Thus, it can be used to study the bridge response for different bridge properties and vehicle speed. The results can be used for any values of bridge properties that yield the frequency parameter.

5 Validation of the proposed model

The model used here to estimate the bridge responses subjected to a moving vehicle is validated with the results obtained from the past available literature. Yang et al. [44] have estimated the dynamic response of a 25 m span simply supported bridge. The model presented in this paper has been used to estimate the response of the same 25 m span bridge used by Yang et al. [44]. Thus, for validation of the model presented in this paper, the mid-point dynamic deflection of the 25 m bridge for a moving force has been estimated. Yang et al. [44] have modeled the vehicle as a moving force without considering the road surface roughness. The data used by Yang et al. [44] is as follows: $E = 2.87 \times 10^6 \text{ kN/m}^2$, the moment of inertia $I = 2.90 \text{ m}^4$, mass per unit length, $\rho = 2303 \text{ kg/m}$ length of bridge $L = 25 \text{ m}$, the mass of the vehicle $m_v = 5750 \text{ kg}$ and stiffness of the vehicle suspension is $k_v = 1595 \text{ kN/m}$. The damping of the vehicle suspension system and the bridge is assumed to be zero. The results obtained by the present model are compared with the results obtained by Yang et al. [44] and shown in Fig. 5. The comparisons of results obtained using our model are in good agreement with the reference model [44]. Hence, the developed model can be used to estimate the dynamic response of simply supported bridges subjected to a moving load.

6 Numerical studies

The numerical studies have been carried out using the moving spring mass damper model. The bridge parameters that are used in this study are given in Table 1 [45–47]. The damping of the bridge is taken as 0.025. The vehicle mass is the same as given by the IRC-06 specification. However, to take into account the effect of road surface roughness the stiffness (K_v) of the spring-mass damper

Fig. 4 Generated road surface roughness

system is taken as 8.28e5 kN/m for IRC class-A loading and 4.968e5 kN/m for IRC class-B loading. Here the value of C_v is considered as zero for both the vehicle loading. The damping ratio for all the bridges is considered as 0.025.

To check the effect of the mass-spring-damper system on the bridge response, the deflection of 25 m bridge obtained using the moving load model and moving spring mass damper model is compared and shown in the Fig. 6. The responses are obtained without

Fig. 5 Verification of the proposed model with the Ref. [44] model

considering the road surface roughness condition (RSC) because the moving load model is unable to take into account the effect of RSC. As it can be seen that both the model gives nearly the same result and hence the consideration of spring stiffness does not make much difference for the bridge response in the absence of RSC.

The bridge response is estimated for IRC class A and B loading and the results are presented in the next section. The bridge response is estimated in terms of deflection, velocity, and acceleration. The impact factor has been estimated using maximum static and dynamic deflection of the bridge. The effect of vehicle speed, span length and RSC on the deflection, velocity, acceleration and impact factor is also estimated and shown in the next sections.

6.1 Case-I: IRC Class-A loading

Table 2 shows the maximum static deflection due to IRC-Class A loading. The deflection of the 20 m span bridge is higher because the flexural rigidity (EI) of the 20 m span bridge is less than the other bridges which indicate that the deflection of the bridge is sensitive to flexural rigidity of the bridge.

Fig. 6 Comparison of the moving load model and moving spring mass damper model at 30 km/h speed

6.1.1 Dynamic deflection of the bridge

The dynamic analysis of the bridges is analyzed under different road surface conditions and vehicle speed. Figure 7a–e shows the midpoint deflection behavior of a 25 m span bridge under different vehicle speeds and road surface conditions. The deflection curves are shown for the vehicle speed of 20 km/h, 40 km/h, 70 km/h, and 100 km/h. As can be seen, the maximum deflection is observed when the vehicle reaches near the midpoint of the bridge and increases with an increase in vehicle speed. At 20 km/h vehicle speed, the deflection curve fluctuates more with less amplitude of variability whereas at 100 km/h speed the fluctuation is less but the amplitude is high. The reason is due to the resonance frequencies of the coupled dynamic system moving vehicle-bridge.

Further, the road surface roughness also plays an important role in the dynamic excitation of the bridge. As can be seen that with the deterioration of road surface condition (RSC) from “Very good” to “Very poor”, the fluctuation of the deflection curve has increased. The amplitude of the fluctuation of the deflection curve is maximum when the road surface condition (RSC) is “Very poor” which indicates

Table 1 Properties of the bridge used in this study

Span Length L (m)	Flexural rigidity EI (N m ²)	Mass per unit length p (kg/m)	Eigen frequencies of the bridge (Hz)									
			1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
20	1.9600×10^9	1000	5.5	22.0	49.5	88.0	137.4	197.9	269.4	351.9	445.3	549.8
23.5	4.000×10^{10}	21,080	3.9	15.7	35.3	62.7	98.0	141.1	192.0	250.8	317.4	391.8
25	2.719×10^{10}	11,150	3.9	15.7	35.3	62.8	98.1	141.3	192.3	251.2	317.9	392.5
30	6.831×10^{10}	12,198	4.1	16.5	37.2	66.1	103.3	148.7	202.4	264.3	334.5	413.0
50	1.562×10^{11}	14,900	2.0	8.1	18.3	32.6	50.9	73.2	99.7	130.2	164.8	203.4
75	4.294×10^{11}	18,650	1.3	5.4	12.1	21.4	33.5	48.2	65.7	85.8	108.5	134.0
100	8.857×10^{11}	22,400	1.0	4.0	8.9	15.8	24.7	35.6	48.4	63.2	80.0	98.8

Table 2 Maximum static deflection response of the bridge in mm

Bridge span	20 m	23.5 m	25 m	30 m	50 m	75 m	100 m
IRC Class-A Loading	46.2138 mm	3.6735 mm	6.5065 mm	4.4752 mm	9.0596 mm	11.1229 mm	12.7828 mm

that the RSC contributes to the amplification of bridge response. A similar trend of variation is observed for all other bridge span and vehicle speed thus, for the sake of brevity they are not shown here.

The maximum deflection of the 25 m bridge for vehicle speed from 20 to 100 km/h is estimated and shown in Fig. 8. As can be seen that the deterioration of RSC causes higher deflection irrespective of vehicle speed. On the other hand, the deflection also increases with an increase in vehicle speed from 20 to 80 km/h. The curve shows some intermediate peaks and depressions before it reaches the maximum value. The intermediate peaks are observed at 40 km/h and 50 km/h, whereas the depressions are observed at 60 km/h and 70 km/h under "Very poor", "Poor", "Average", "Very good" and "Good" RSC. The drop of deflection is observed at some intermediate speed which is due to the phenomena of cancellation [48].

The maximum deflection for different span and road surface condition is estimated and compared in Fig. 9. Here a random vehicle speed of 40 km/h is selected to show the results. Table 2 shows the deflection values for different RSC and bridge span. The deflection increases with deterioration of RSC irrespective of the bridge span. The minimum and maximum deflection are observed for "Very good" and "Very poor" RSC respectively. The minimum deflection for bridge span of 20 m, 23.5 m, 25 m, 30 m, 50 m, 75 m, and 100 m are 51.76 mm, 4.19 mm, 7.31 mm, 4.75 mm, 9.19 mm, 12.89 mm and 14.63 mm respectively. On the other hand, the maximum deflection for bridge span of 20 m, 23.5 m, 25 m, 30 m, 50 m, 75 m, and 100 m is 115.89 mm, 9.81 mm, 16.97 mm, 10.53 mm, 15.31 mm, 31.57 mm and 39.42 mm respectively.

6.1.1.1 Dynamic velocity response of the bridge The maximum velocity response of 25 m bridge for different vehicle speeds and RSC is shown in Fig. 10. As can be seen that the bridge velocity response increases with an increase in vehicle speed and road surface conditions. The maximum velocity of the bridge is observed at 100 km/h speed under different road surface conditions. The maximum velocity of bridge observed under "Very good", "Good", "Average", "Poor" and "Very poor" road surface condition are 0.05 m/s, 0.05 m/s, 0.06 m/s, 0.08 m/s and 0.12 m/s respectively. A similar trend of variation is observed for all other different spans of the bridge and thus is not shown.

To study the effect of the bridge span on the velocity response of the bridge, a comparison of the maximum velocity of the bridges is shown in Fig. 11. The responses are computed at 40 km/h vehicle speed. It can be seen that the velocity response of the bridge decreases when the span increases from 50 to 100 m. However, the trend is not similar for lower span lengths up to 50 m. On the other hand, the velocity of the bridge increases with deterioration of RSC irrespective of span length.

6.1.1.2 Dynamic vertical acceleration of the bridge Figure 12 shows the vertical acceleration of the 25 m bridge under different RSC and vehicle speed. The maximum acceleration under "Very good", "Good", "Average", "Poor" and "Very poor" RSC is observed at 80 km/h. It indicates that the deterioration of RSC from the vertical acceleration gets magnified at lower vehicle speed. The maximum acceleration observed under "Very good", "Good", "Average", "Poor" and "Very poor" road surface condition are 0.96 m/s^2 , 1.00 m/s^2 , 1.08 m/s^2 , 1.25 m/s^2 and 1.59 m/s^2 respectively. Figure 13 shows the maximum vertical acceleration of the 25 m bridges at 40 km/h speed. It can be observed that the increase in span length causes a decrease in vertical acceleration except for a 25 m bridge where the acceleration response is greater than the maximum acceleration response of 23.5 m bridge. This indicates that the acceleration response is directly proportional to the stiffness of the bridge. Figure 14 shows the frequency spectrum of acceleration response of 25 m bridge due to vehicle moving at 30 km/h speed. The responses are compared to different road surface conditions. It can be observed that the deterioration of road surface conditions causes the higher amplitude of bridge response however it does not cause excitation of other modes of the bridge. The excited bridge frequency which can be identified is 3.92 Hz as observed from Fig. 14. On the other hand, an increase in vehicle speed can excite the different frequencies corresponding to bridge modes as shown in Fig. 15.

6.1.1.3 Case-II: IRC Class B loading The IRC Class B loading has 40.07% less weight than the IRC Class A loading. Thus, the spring stiffness of the vehicle is also reduced in the same ratio. Here the value of vehicle spring stiffness (K_v) is considered as 4.968e5 kN/m .

Fig. 7 Midspan deflection of 25 m bridge under different road surface condition and vehicle speed due to IRC Class A loading

Fig. 8 Maximum deflection of 25 m bridge under different road surface condition and vehicle speed due to IRC Class A loading

Fig. 9 Comparison of maximum deflection for different bridge span and road surface conditions at 40 km/h vehicle speed due to IRC Class A loading

Fig. 10 Maximum velocity of 25 m bridge under different road surface condition due to IRC Class A loading

Table 3 shows the maximum static deflection due to IRC-Class B loading. All the parameters under study show a similar trend as observed in IRC Class A loading with variation only in the magnitude of values thus they are

not shown here. However, the obtained results have been presented in "Appendix".

From the above results obtained in Sects. 6.1 and 6.2, it has been observed that the deflection, velocity, and

Fig. 11 Comparison of the maximum velocity of bridges under different road surface conditions at 40 km/h speed due to IRC Class A loading

Fig. 12 Maximum vertical acceleration of 25 m bridge under different road surface condition due to IRC Class A loading

Fig. 13 Comparison of maximum acceleration of bridges under different road surface conditions at 40 km/h speed due to IRC Class A loading

acceleration of the 20 m span bridge is much higher as compared to other bridges. This is because the flexural rigidity (EI) of the 20 m span bridge is much less than the other bridges considered in this study. Thus, it is evident that the deflection, velocity and acceleration response of the bridge is sensitive to the EI parameter. The maximum

deflection, velocity, and acceleration of all the bridges under different road surface conditions and the vehicle speed are presented in Tables 6, 7, 8, 9, 10 and 11 of "Appendix" and the corresponding maximum values have been highlighted.

Fig. 14 Frequency spectrum of acceleration of 25 m bridge under different road surface conditions at 30 km/h speed due to IRC Class A loading

Fig. 15 Comparison of the frequency spectrum of acceleration of 25 m bridges under "Very good" road surface condition at 20 km/h, 40 km/h, 70 km/h, and 100 km/h speed due to IRC Class A loading

Table 3 Static deflection of bridges due to IRC Class-B loading

Bridge span	20 m	23.5 m	25 m	30 m	50 m	75 m	100 m
IRC Class-B Loading	27.6949 mm	2.2015 mm	3.8992 mm	2.6819 mm	5.4292 mm	6.6657 mm	7.6605 mm

7 Impact factor due to IRC Class A and Class B loading

The impact factor is estimated using the maximum static and dynamic deflection of the bridge. The impact factor for both the loading condition is the same. Figure 16 shows the variation of the impact factor of bridges for different span lengths, road surface conditions, and vehicle speed. The impact factor is plotted separately for different bridge span. From the figure, it is observed that the impact factor increases when the road surface condition deteriorates from "very good" to "very poor". At the same time, the impact factor also increases with an increase in vehicle speed. However, a drop in impact factor is observed for certain intermediate vehicle speed. On the other hand, Fig. 17 shows that the impact factor of 23.5 m span

is higher than the impact factor obtained for the 20 m span bridge which shows that the impact factor may not decrease with an increase in span. The impact factor may even reach greater than 1 when the road surface condition is "Very poor". The bridge response in presence of RSC initially increases and then it starts decreasing at higher vehicle speed. The vehicle speed after which the response starts decreasing is changing with the span of the bridge. As can be observed that the variation of the impact factor is different for different bridge span and vehicle speed. However, both the parameter has a significant effect on the peak response of the bridge.

Fig. 16 Impact factor of bridges under different RSC and vehicle speed due to IRC Class A and B loading

Fig. 17 Comparison of maximum impact factor of bridges due to IRC Class-A and B loading under different RSC

Table 4 Different frequency ratios for vehicle speed between 20 and 100 km/h and bridge span between 20 and 100 m

Vehicle speed in km/h	Bridge span						
	20 m	23.5 m	25 m	30 m	50 m	75 m	100 m
	Frequency ratio (S_1)						
30	0.0379	0.0453	0.0425	0.0336	0.0410	0.0415	0.0422
40	0.0505	0.0603	0.0566	0.0448	0.0546	0.0553	0.0562
50	0.0632	0.0754	0.0708	0.0560	0.0683	0.0691	0.0703
60	0.0758	0.0905	0.0849	0.0673	0.0819	0.0829	0.0844
70	0.0884	0.1056	0.0991	0.0785	0.0956	0.0967	0.0984
80	0.1011	0.1207	0.1132	0.0897	0.1092	0.1106	0.1125
90	0.1137	0.1358	0.1274	0.1009	0.1229	0.1244	0.1265
100	0.1263	0.1508	0.1416	0.1121	0.1365	0.1382	0.1406

Fig. 18 Impact factor with the change in the frequency parameter

8 Variation of impact factor with the change in the frequency ratio

In the previous section, it has been observed that the variation of the impact factor is the same for both the IRC Class A and B loading cases. In this section, the effect of the frequency parameter on the impact factor of the bridge is

investigated. The frequency parameter is estimated using the vehicle driving frequency and fundamental frequency of the bridge. The frequency and vehicle speed are varied to obtain the different values of the frequency parameter. The frequency parameters obtained considering the vehicle speed between 20 and 100 km/h and bridge span between 20 and 100 m is shown in Table 4. However, the S_1 values are varied up to 1.4 by varying the vehicle speed

Fig. 19 Comparison of maximum impact factor with IRC-06 specification **Table 5** Comparison of maximum Impact factor values obtained considering the different RSC and vehicle speed with IRC-06 specification

Bridge span	IRC-06 specification	Road surface roughness condition				
		"Very good"	"Good"	"Average"	"Poor"	"Very poor"
Impact factor of bridges						
20 m	0.1731	0.1743	0.2604	0.4668	0.8821	1.7142
23.5 m	0.1525	0.2182	0.3211	0.5400	0.9779	1.8537
25 m	0.1452	0.1887	0.2835	0.4959	0.9209	1.7711
30 m	0.1250	0.1566	0.2172	0.3693	0.7536	1.5299

and bridge frequency to plot the variation of impact factor. Figure 18 shows the variation of impact factor with a change in the frequency parameter under different road surface conditions. As it can be seen that the impact factor for all RSC reaches a maximum when the S_1 value is 0.4. Thus, in design, the resonant point i.e. $S_1 = 0.4$ should be avoided. The curve shows some intermediate peaks before S_1 reaches its maximum value of 0.4. The bridge's fundamental frequency decreases due to the added mass effect and thus the critical resonance condition occurs at S_1 values less than 1. A higher value of S_1 represents that either the vehicle is moving at higher speed or the frequency of the bridge is less. As the frequency of the bridge is a function of span length and it is a non-dimensional parameter thus it can apply to bridges with different cross-sectional properties for impact factor determination.

9 Comparison with IRC-06 specification

As per the IRC-6 specifications, the impact factor for concrete bridges is estimated using Eq. (1). This equation is only valid for bridge span length up to 45 m. Therefore, the impact factor obtained in this study for 20 m, 23.5 m, 25 m, and 30 m bridges is compared with the impact factor suggested by IRC-6 specification. The maximum impact factor obtained considering the vehicle speed

and road surface roughness condition (RSC) is compared with the impact factor values suggested in IRC-06 specification and shown in Fig. 19 and Table 5. It is clear from the figure that IRC-06 underestimates the impact factor values. It is clear from the figure that, the speed of the vehicle and road surface roughness condition plays an important role in magnifying the impact factor which is neglected in IRC-06 specification. Thus, due consideration should be made for vehicle speed and road surface roughness in estimating the impact factor for bridges.

10 Conclusions

A parametric study on bridge responses and impact factor to specify the effects of span length, vehicle speed and road surface roughness have been conducted. Dynamic responses and impact factors have been calculated for a simply supported bridge loaded with two types of vehicular load viz. IRC class A and class B. The vehicles were idealized as a series of moving mass spring damper system. The vehicle-bridge interaction was modeled using the coupled equation of motion and was solved by Newmark's beta method. Various speeds of vehicle ranging from 20 to 100 km/h was considered for the study.

The obtained research results, when compared with IRC-06 specification, shows that in most of the cases the impact factor values proposed by design code are underestimated. In the current design codes, the impact factor relations have been defined just based on span length, where there is a decrease with an increase in span length. But the results of the research show that in some conditions impact factors for bridges with a longer span length are greater than those for shorter ones.

The research results also show that vehicle speed and road surface roughness are also effective parameters in impact factor. According to achieved results, conditions for impact factors are different in different velocity ranges. The results show that with the increase in vehicle speed from 30 to 100 km/h causes an increase in impact factor values with intermediate peaks and depressions depending on the bridge span. Hence, a parameter which includes both vehicle speed and bridge span can be a better indicator of the impact factor. The curve obtained for impact factor with respect to frequency ratio which includes both bridge frequency and vehicle speed can be considered as a modification of IRC-06 specification for accurate estimation of the impact factor of simply supported bridges. It is also observed that the maximum impact factor is obtained for the frequency ratio value of 0.4 irrespective of the road surface condition. Thus, in the design, this value should be avoided. The RSC also influences impact factor and it is seen that with deteriorated RSC, the impact factor increases drastically. Hence, to avoid high impact factor values, the RSC must be maintained at “good” or “very good” condition.

In this research, according to dynamic analysis results, it is observed that the increase in span length causes a

decrease in vertical acceleration, except for a 25 m bridge where the acceleration response is greater than the maximum acceleration response of 23.5 m bridge. This indicates that the acceleration response is directly proportional to the stiffness of the bridge. The road surface roughness affects the deflection, velocity, and acceleration of the bridge for varying speeds.

In the present study, the bridge response and Impact factor values are obtained considering the bridge as simply supported. Further research can be carried out to study the bridge response and impact factor for continuous bridges subjected to IRC class A and B vehicles. Also, in the present study, the vehicle is considered to be moving with constant speed. Thus, further studies may be done with varying vehicle speeds.

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Data availability statement All data, models, and code generated or used during the study appear in the submitted article.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Appendix

See Tables 6, 7, 8, 9, 10 and 11.

Table 6 Maximum deflection of bridges under different road surface condition and vehicle speed due to IRC Class A loading

Road surface condition (RSC)	Vehicle speed (km/h)	Bridge span						
		20 m	23.5 m	25 m	30 m	50 m	75 m	100 m
		Displacement response of bridge in mm						
"Very good"	30	52.5894	4.1042	7.0860	4.9402	9.6651	12.4725	14.3362
	40	51.7563	4.1879	7.3114	4.7455	9.1908	12.8908	14.6328
	50	52.4375	4.1389	7.3556	4.6912	9.3900	13.1009	14.1603
	60	51.1688	4.1672	7.2823	5.0116	10.1664	12.5772	15.3044
	70	53.9310	4.2745	7.6915	5.0234	9.5562	13.4486	14.1443
	80	53.9993	4.4520	7.6598	5.1762	9.6547	13.3072	15.1827
	90	51.5225	4.4752	7.7340	4.8594	10.4588	12.6653	16.1816
"Good"	100	54.2680	4.3284	7.5971	4.8483	10.7458	13.7676	16.0743
	30	57.3054	4.4731	7.7240	5.3046	9.9448	13.7320	15.6634
	40	55.0371	4.5507	7.8771	5.0269	9.3531	14.0672	16.2855
	50	55.7742	4.5079	7.8880	5.0317	9.5573	14.2965	15.5881
	60	54.1701	4.3234	7.5535	5.2672	10.5987	13.9655	16.9937
	70	58.2458	4.5882	8.2588	5.3907	9.5999	14.7878	14.6290
	80	58.2130	4.8530	8.3510	5.4473	9.7851	14.7830	16.7135
"Average"	90	53.4471	4.8228	8.3305	5.2475	10.9014	12.9814	17.9677
	100	57.6354	4.4877	8.0603	5.0801	11.0568	14.8360	17.5624
	30	66.7824	5.2123	9.0026	6.0335	10.6277	16.2508	18.3178
	40	62.6201	5.2969	9.1695	5.7119	10.1125	16.4199	19.5910
	50	62.6627	5.2527	9.0604	5.7173	10.0947	16.6875	18.4436
	60	62.4290	4.8967	8.5106	5.7857	11.4632	16.7523	20.3722
	70	67.7849	5.2186	9.3934	6.1281	10.1398	17.5003	17.2021
"Poor"	80	67.6515	5.6571	9.7334	6.0253	10.1526	17.7427	19.8153
	90	58.0608	5.6115	9.6820	6.1115	11.7865	14.8607	21.5924
	100	64.4828	5.0953	9.1572	5.7723	11.9570	17.3173	20.8237
	30	85.7363	6.6933	11.5598	7.4913	12.2307	21.3488	24.2705
	40	80.3594	6.7994	11.7656	7.2964	11.6313	21.4293	26.2019
	50	80.3835	6.7425	11.6340	7.0974	11.4184	21.4696	24.1710
	60	80.0699	6.2756	10.9062	7.2491	13.1921	22.3287	27.1292
"Very Poor"	70	86.9780	6.4794	11.6626	7.6088	11.3835	22.9255	22.9834
	80	86.7831	7.2658	12.4981	7.4732	11.6774	23.7299	26.5019
	90	74.5712	7.2020	12.4233	7.8477	13.5587	19.8073	28.8787
	100	81.2996	6.3694	11.3579	7.3096	13.7605	22.2799	27.7305
	30	123.6734	9.6571	16.6741	10.4069	15.4366	32.1217	36.5178
	40	115.8900	9.8057	16.9709	10.5265	15.3064	31.5715	39.4238
	50	115.9247	9.7252	16.7812	9.8597	16.2065	31.6304	36.3680
	60	115.4850	9.0480	15.7192	10.4449	16.7848	33.4813	40.6433
	70	125.4350	9.0011	16.2010	10.5701	15.0225	33.7757	34.5811
	80	125.1697	10.4831	18.0303	10.6497	16.1461	35.7044	39.8752
	90	107.5920	10.3863	17.9159	11.3219	17.1128	29.7006	43.4513
	100	117.2458	9.1818	15.9266	10.5320	17.3892	32.2050	41.5440

Table 7 Maximum velocity response of bridges under different road surface condition and vehicle speed due to IRC Class A loading

Road surface condition (RSC)	Vehicle speed (km/h)	Bridge span						
		20 m	23.5 m	25 m	30 m	50 m	75 m	100 m
		Velocity response of bridge in m/s						
"Very good"	30	0.1251	0.0085	0.0143	0.0080	0.0101	0.0083	0.0071
	40	0.1662	0.0113	0.0188	0.0108	0.0136	0.0112	0.0095
	50	0.2095	0.0138	0.0229	0.0132	0.0170	0.0139	0.0116
	60	0.2573	0.0175	0.0291	0.0166	0.0205	0.0170	0.0143
	70	0.2858	0.0197	0.0328	0.0188	0.0236	0.0190	0.0168
	80	0.3458	0.0226	0.0375	0.0220	0.0266	0.0226	0.0192
	90	0.3815	0.0258	0.0429	0.0242	0.0310	0.0251	0.0217
"Good"	100	0.4124	0.0297	0.0494	0.0281	0.0343	0.0277	0.0245
	30	0.1330	0.0092	0.0153	0.0085	0.0110	0.0091	0.0076
	40	0.1756	0.0121	0.0200	0.0116	0.0149	0.0123	0.0104
	50	0.2234	0.0143	0.0238	0.0136	0.0187	0.0152	0.0124
	60	0.2788	0.0190	0.0317	0.0181	0.0228	0.0188	0.0155
	70	0.2964	0.0207	0.0345	0.0199	0.0260	0.0202	0.0184
	80	0.3767	0.0237	0.0396	0.0236	0.0288	0.0249	0.0210
"Average"	90	0.4068	0.0275	0.0456	0.0255	0.0343	0.0273	0.0237
	100	0.4285	0.0324	0.0539	0.0306	0.0374	0.0302	0.0272
	30	0.1490	0.0104	0.0174	0.0094	0.0129	0.0107	0.0088
	40	0.1944	0.0135	0.0224	0.0130	0.0176	0.0145	0.0121
	50	0.2515	0.0153	0.0255	0.0146	0.0223	0.0179	0.0139
	60	0.3228	0.0221	0.0368	0.0211	0.0274	0.0226	0.0181
	70	0.3175	0.0227	0.0379	0.0222	0.0311	0.0228	0.0217
"Poor"	80	0.4386	0.0267	0.0448	0.0268	0.0336	0.0294	0.0244
	90	0.4576	0.0308	0.0511	0.0282	0.0413	0.0319	0.0277
	100	0.4642	0.0378	0.0628	0.0357	0.0437	0.0352	0.0327
	30	0.1808	0.0129	0.0216	0.0112	0.0165	0.0139	0.0111
	40	0.2320	0.0165	0.0273	0.0159	0.0230	0.0193	0.0156
	50	0.3090	0.0173	0.0289	0.0169	0.0297	0.0232	0.0170
	60	0.4109	0.0282	0.0471	0.0270	0.0365	0.0301	0.0238
"Very Poor"	70	0.3598	0.0268	0.0449	0.0266	0.0415	0.0279	0.0283
	80	0.5624	0.0329	0.0553	0.0333	0.0432	0.0386	0.0313
	90	0.5597	0.0373	0.0619	0.0342	0.0552	0.0422	0.0356
	100	0.5458	0.0485	0.0806	0.0458	0.0564	0.0452	0.0437
	30	0.2446	0.0178	0.0299	0.0149	0.0239	0.0203	0.0160
	40	0.3071	0.0229	0.0376	0.0217	0.0339	0.0289	0.0226
	50	0.4265	0.0213	0.0357	0.0217	0.0445	0.0339	0.0233
	60	0.5873	0.0405	0.0678	0.0388	0.0548	0.0453	0.0356
	70	0.4444	0.0353	0.0590	0.0357	0.0623	0.0380	0.0415
	80	0.8099	0.0454	0.0765	0.0462	0.0625	0.0568	0.0450
	90	0.7638	0.0537	0.0886	0.0462	0.0829	0.0632	0.0515
	100	0.7130	0.0700	0.1164	0.0661	0.0817	0.0653	0.0658

Table 8 Maximum acceleration response of bridges under different road surface condition and vehicle speed due to IRC Class A loading

Road surface condition (RSC)	Vehicle speed (km/h)	Bridge span						
		20 m	23.5 m	25 m	30 m	50 m	75 m	100 m
		Acceleration response of bridge in m/s ²						
"Very good"	30	3.4353	0.1622	0.2664	0.1659	0.0986	0.0549	0.0340
	40	4.6059	0.2348	0.3697	0.2244	0.1356	0.0767	0.0463
	50	5.7508	0.2868	0.4752	0.2765	0.1725	0.0923	0.0591
	60	6.8716	0.3437	0.5703	0.3387	0.2035	0.1129	0.0726
	70	8.3960	0.3977	0.6421	0.3885	0.2391	0.1368	0.0794
	80	9.6363	0.4900	0.7961	0.4590	0.2856	0.1513	0.0966
	90	10.5189	0.5424	0.8733	0.4980	0.3077	0.1636	0.1142
	100	12.1626	0.5714	0.9557	0.5667	0.3514	0.2012	0.1185
"Good"	30	3.6936	0.1695	0.2833	0.1763	0.1045	0.0591	0.0373
	40	4.9331	0.2541	0.3946	0.2386	0.1500	0.0835	0.0495
	50	6.0613	0.3050	0.5047	0.2925	0.1882	0.0987	0.0639
	60	7.1682	0.3549	0.5912	0.3527	0.2207	0.1216	0.0789
	70	8.9280	0.4176	0.6779	0.4110	0.2658	0.1498	0.0821
	80	10.1899	0.5294	0.8601	0.4826	0.3133	0.1673	0.1049
	90	10.8306	0.5695	0.9144	0.5427	0.3346	0.1698	0.1235
	100	12.8866	0.5745	0.9980	0.5861	0.3751	0.2144	0.1240
"Average"	30	4.2101	0.1947	0.3170	0.2012	0.1213	0.0683	0.0447
	40	5.5876	0.2928	0.4445	0.2671	0.1788	0.0972	0.0561
	50	6.6822	0.3416	0.5635	0.3246	0.2197	0.1154	0.0733
	60	7.8698	0.3861	0.6331	0.3902	0.2549	0.1418	0.0916
	70	9.9921	0.4573	0.7495	0.4791	0.3190	0.1758	0.0968
	80	11.2975	0.6080	0.9881	0.5298	0.3687	0.1995	0.1217
	90	11.9882	0.6283	1.0101	0.6320	0.3891	0.1867	0.1446
	100	14.6508	0.6208	1.0826	0.6264	0.4427	0.2409	0.1440
"Poor"	30	5.2758	0.2451	0.3844	0.2551	0.1548	0.0903	0.0595
	40	6.8965	0.3702	0.5605	0.3239	0.2364	0.1245	0.0713
	50	8.3015	0.4146	0.6832	0.3888	0.2826	0.1506	0.0932
	60	9.2731	0.4547	0.7558	0.4670	0.3234	0.1829	0.1170
	70	12.1202	0.5368	0.8943	0.6153	0.4255	0.2278	0.1264
	80	13.5127	0.7654	1.2440	0.6242	0.4795	0.2638	0.1553
	90	15.3556	0.7458	1.2254	0.8108	0.4982	0.2347	0.1884
	100	18.1793	0.7217	1.2517	0.7104	0.5896	0.2939	0.1841
"Very Poor"	30	7.5984	0.3458	0.5265	0.3628	0.2219	0.1343	0.0892
	40	9.5143	0.5249	0.8063	0.4547	0.3516	0.1792	0.1018
	50	11.6596	0.5608	0.9240	0.5172	0.4085	0.2209	0.1335
	60	12.5957	0.6256	1.0379	0.6205	0.4604	0.2651	0.1677
	70	16.3765	0.7129	1.2093	0.8877	0.6385	0.3327	0.1855
	80	17.9430	1.0881	1.7560	0.8252	0.7011	0.3924	0.2231
	90	22.0906	1.0240	1.6977	1.1682	0.7163	0.3390	0.2761
	100	25.2363	0.9515	1.5900	0.9512	0.8832	0.4169	0.2756

Table 9 Maximum deflection of bridges under different road surface condition and vehicle speed due to IRC Class B loading

Road surface condition (RSC)	Vehicle speed (km/h)	Bridge span						
		20 m	23.5 m	25 m	30 m	50 m	75 m	100 m
		Deflection response of bridge in mm						
"Very good"	30	31.5157	2.4596	4.2465	2.9605	5.7921	7.4745	8.5914
	40	31.0164	2.5097	4.3816	2.8439	5.5078	7.7252	8.7691
	50	31.4246	2.4804	4.4081	2.8113	5.6272	7.8511	8.4860
	60	30.6643	2.4973	4.3641	3.0033	6.0925	7.5373	9.1716
	70	32.3196	2.5616	4.6094	3.0104	5.7268	8.0594	8.4764
	80	32.3606	2.6680	4.5904	3.1020	5.7858	7.9747	9.0986
	90	30.8763	2.6819	4.6348	2.9121	6.2677	7.5900	9.6973
"Good"	100	32.5216	2.5939	4.5528	2.9055	6.4398	8.2506	9.6330
	30	34.3418	2.6806	4.6288	3.1789	5.9597	8.2293	9.3867
	40	32.9825	2.7272	4.7206	3.0125	5.6051	8.4302	9.7595
	50	33.4242	2.7015	4.7271	3.0154	5.7275	8.5676	9.3416
	60	32.4629	2.5909	4.5267	3.1565	6.3515	8.3692	10.1839
	70	34.9054	2.7496	4.9493	3.2305	5.7530	8.8620	8.7668
	80	34.8857	2.9083	5.0046	3.2644	5.8640	8.8591	10.0160
"Average"	90	32.0297	2.8902	4.9923	3.1447	6.5330	7.7795	10.7677
	100	34.5396	2.6894	4.8303	3.0444	6.6261	8.8909	10.5247
	30	40.0212	3.1236	5.3950	3.6157	6.3689	9.7388	10.9774
	40	37.5268	3.1743	5.4951	3.4230	6.0602	9.8401	11.7404
	50	37.5523	3.1478	5.4297	3.4263	6.0496	10.0005	11.0528
	60	37.4123	2.9345	5.1002	3.4672	6.8696	10.0393	12.2086
	70	40.6219	3.1274	5.6293	3.6724	6.0765	10.4876	10.3088
"Poor"	80	40.5420	3.3902	5.8330	3.6108	6.0842	10.6328	11.8749
	90	34.7945	3.3629	5.8022	3.6625	7.0634	8.9057	12.9398
	100	38.6431	3.0535	5.4877	3.4592	7.1656	10.3779	12.4792
	30	51.3798	4.0111	6.9275	4.4894	7.3296	12.7938	14.5448
	40	48.1575	4.0747	7.0509	4.3726	6.9704	12.8421	15.7022
	50	48.1720	4.0406	6.9720	4.2533	6.8428	12.8663	14.4851
	60	47.9840	3.7608	6.5358	4.3442	7.9058	13.3810	16.2579
"Very Poor"	70	52.1239	3.8830	6.9891	4.5598	6.8218	13.7387	13.7734
	80	52.0071	4.3542	7.4898	4.4785	6.9980	14.2208	15.8820
	90	44.6888	4.3160	7.4450	4.7029	8.1254	11.8701	17.3063
	100	48.7210	3.8170	6.8065	4.3804	8.2464	13.3518	16.6182
	30	74.1145	5.7873	9.9924	6.2366	9.2508	19.2498	21.8842
	40	69.4501	5.8763	10.1702	6.3083	9.1727	18.9201	23.6258
	50	69.4709	5.8281	10.0566	5.9087	9.7122	18.9554	21.7945
	60	69.2074	5.4222	9.4202	6.2594	10.0587	20.0645	24.3566
	70	75.1702	5.3941	9.7089	6.3344	9.0026	20.2410	20.7236
	80	75.0112	6.2823	10.8052	6.3821	9.6760	21.3968	23.8963
	90	64.4773	6.2243	10.7366	6.7850	10.2553	17.7989	26.0394
	100	70.2627	5.5024	9.5445	6.3116	10.4210	19.2997	24.8963

Table 10 Maximum velocity response of bridges under different road surface condition and vehicle speed due to IRC Class B loading

Road surface condition (RSC)	Vehicle speed (km/h)	Bridge span						
		20 m	23.5 m	25 m	30 m	50 m	75 m	100 m
		Velocity response of bridge in m/s						
"Very good"	30	0.0750	0.0051	0.0085	0.0048	0.0061	0.0050	0.0042
	40	0.0996	0.0068	0.0113	0.0065	0.0081	0.0067	0.0057
	50	0.1255	0.0083	0.0137	0.0079	0.0102	0.0083	0.0070
	60	0.1542	0.0105	0.0174	0.0100	0.0123	0.0102	0.0085
	70	0.1713	0.0118	0.0196	0.0113	0.0142	0.0114	0.0101
	80	0.2072	0.0135	0.0225	0.0132	0.0159	0.0135	0.0115
	90	0.2286	0.0155	0.0257	0.0145	0.0186	0.0150	0.0130
	100	0.2471	0.0178	0.0296	0.0168	0.0206	0.0166	0.0147
"Good"	30	0.0797	0.0055	0.0092	0.0051	0.0066	0.0055	0.0046
	40	0.1052	0.0072	0.0120	0.0069	0.0089	0.0074	0.0062
	50	0.1339	0.0086	0.0142	0.0082	0.0112	0.0091	0.0074
	60	0.1671	0.0114	0.0190	0.0108	0.0137	0.0113	0.0093
	70	0.1776	0.0124	0.0207	0.0120	0.0156	0.0121	0.0110
	80	0.2257	0.0142	0.0237	0.0141	0.0173	0.0149	0.0126
	90	0.2438	0.0165	0.0273	0.0153	0.0206	0.0164	0.0142
	100	0.2568	0.0194	0.0323	0.0184	0.0224	0.0181	0.0163
"Average"	30	0.0893	0.0062	0.0104	0.0056	0.0077	0.0064	0.0053
	40	0.1165	0.0081	0.0134	0.0078	0.0105	0.0087	0.0073
	50	0.1507	0.0092	0.0153	0.0088	0.0134	0.0107	0.0083
	60	0.1934	0.0132	0.0220	0.0126	0.0164	0.0135	0.0108
	70	0.1903	0.0136	0.0227	0.0133	0.0187	0.0137	0.0130
	80	0.2628	0.0160	0.0268	0.0161	0.0201	0.0176	0.0146
	90	0.2743	0.0184	0.0306	0.0169	0.0247	0.0191	0.0166
	100	0.2782	0.0226	0.0376	0.0214	0.0262	0.0211	0.0196
"Poor"	30	0.1084	0.0077	0.0129	0.0067	0.0099	0.0083	0.0067
	40	0.1390	0.0099	0.0164	0.0095	0.0138	0.0116	0.0094
	50	0.1852	0.0104	0.0173	0.0101	0.0178	0.0139	0.0102
	60	0.2463	0.0169	0.0282	0.0162	0.0219	0.0181	0.0142
	70	0.2156	0.0161	0.0269	0.0159	0.0248	0.0167	0.0170
	80	0.3370	0.0197	0.0331	0.0199	0.0259	0.0231	0.0187
	90	0.3354	0.0224	0.0371	0.0205	0.0331	0.0253	0.0214
	100	0.3271	0.0291	0.0483	0.0275	0.0338	0.0271	0.0262
"Very Poor"	30	0.1466	0.0107	0.0179	0.0089	0.0143	0.0122	0.0096
	40	0.1841	0.0137	0.0225	0.0130	0.0203	0.0173	0.0135
	50	0.2556	0.0128	0.0214	0.0130	0.0267	0.0203	0.0139
	60	0.3519	0.0243	0.0406	0.0233	0.0328	0.0272	0.0213
	70	0.2663	0.0212	0.0353	0.0214	0.0374	0.0228	0.0249
	80	0.4854	0.0272	0.0458	0.0277	0.0374	0.0341	0.0270
	90	0.4577	0.0322	0.0531	0.0277	0.0497	0.0379	0.0309
	100	0.4273	0.0419	0.0697	0.0396	0.0490	0.0391	0.0394

Table 11 Maximum acceleration response of bridges under different road surface condition and vehicle speed due to IRC Class B loading

Road surface condition (RSC)	Vehicle speed (km/h)	Bridge span						
		20 m	23.5 m	25 m	30 m	50 m	75 m	100 m
		Acceleration response of bridge in m/s ²						
"Very good"	30	2.0587	0.0972	0.1596	0.0994	0.0591	0.0329	0.0204
	40	2.7602	0.1407	0.2215	0.1345	0.0812	0.0459	0.0278
	50	3.4463	0.1719	0.2848	0.1657	0.1034	0.0553	0.0354
	60	4.1180	0.2060	0.3418	0.2030	0.1220	0.0676	0.0435
	70	5.0315	0.2383	0.3848	0.2328	0.1433	0.0820	0.0476
	80	5.7748	0.2937	0.4771	0.2751	0.1711	0.0907	0.0579
	90	6.3037	0.3250	0.5233	0.2985	0.1844	0.0981	0.0684
	100	7.2888	0.3424	0.5728	0.3396	0.2106	0.1206	0.0710
"Good"	30	2.2135	0.1016	0.1697	0.1056	0.0626	0.0354	0.0223
	40	2.9563	0.1523	0.2365	0.1430	0.0899	0.0500	0.0297
	50	3.6324	0.1828	0.3024	0.1753	0.1128	0.0591	0.0383
	60	4.2957	0.2127	0.3543	0.2114	0.1322	0.0729	0.0473
	70	5.3504	0.2502	0.4063	0.2463	0.1593	0.0898	0.0492
	80	6.1066	0.3172	0.5154	0.2892	0.1877	0.1003	0.0629
	90	6.4905	0.3413	0.5480	0.3252	0.2005	0.1018	0.0740
	100	7.7227	0.3443	0.5981	0.3512	0.2248	0.1285	0.0743
"Average"	30	2.5230	0.1167	0.1899	0.1206	0.0727	0.0409	0.0268
	40	3.3485	0.1755	0.2664	0.1600	0.1071	0.0582	0.0336
	50	4.0045	0.2047	0.3377	0.1945	0.1317	0.0691	0.0440
	60	4.7162	0.2314	0.3794	0.2339	0.1528	0.0850	0.0549
	70	5.9880	0.2741	0.4492	0.2871	0.1912	0.1054	0.0580
	80	6.7703	0.3644	0.5921	0.3175	0.2209	0.1196	0.0729
	90	7.1842	0.3765	0.6053	0.3788	0.2332	0.1119	0.0866
	100	8.7799	0.3720	0.6488	0.3754	0.2653	0.1444	0.0863
"Poor"	30	3.1617	0.1469	0.2303	0.1529	0.0928	0.0541	0.0357
	40	4.1329	0.2218	0.3359	0.1941	0.1417	0.0746	0.0428
	50	4.9749	0.2485	0.4094	0.2330	0.1694	0.0902	0.0558
	60	5.5571	0.2725	0.4529	0.2799	0.1938	0.1096	0.0701
	70	7.2634	0.3217	0.5359	0.3687	0.2550	0.1365	0.0757
	80	8.0978	0.4587	0.7455	0.3741	0.2873	0.1581	0.0931
	90	9.2023	0.4470	0.7343	0.4859	0.2985	0.1407	0.1129
	100	10.8945	0.4325	0.7501	0.4257	0.3533	0.1761	0.1103
"Very Poor"	30	4.5535	0.2072	0.3155	0.2174	0.1330	0.0805	0.0535
	40	5.7017	0.3146	0.4832	0.2725	0.2107	0.1074	0.0610
	50	6.9873	0.3361	0.5538	0.3099	0.2448	0.1324	0.0800
	60	7.5483	0.3749	0.6220	0.3719	0.2759	0.1589	0.1005
	70	9.8140	0.4272	0.7247	0.5320	0.3827	0.1994	0.1112
	80	10.7528	0.6521	1.0523	0.4945	0.4201	0.2351	0.1337
	90	13.2384	0.6137	1.0174	0.7001	0.4293	0.2032	0.1655
	100	15.1235	0.5702	0.9529	0.5701	0.5293	0.2498	0.1651

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